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14. ABSTRACT

This presentation examines the background of transverse jets and their problems, parameters and design space. Apparatus is discussed, including water flow loop and test section parts, as well as flow measurements, LDV, PLIF, and results, Holdeman Scaling and unmixedness.

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Project Themis: Water Visualization Study

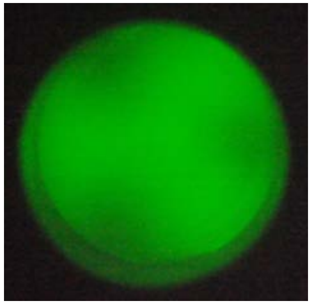
Allen Bishop
AFRL/RZSE
15 Sept 2011

About Me

- BS & MS Aerospace Engineering
  Cal Poly, San Luis Obispo
- Work Experience
  - AFFTC/812 TSS Eng. Outreach
    (June-Sept 2009)
  - AFRL Themis Co-Op
    (Apr 2010-Sept 2011)
  - Florida Turbine Technologies – Aero/Heat Xfer
    (Oct 2011 – future)
- Hobbies
  - Guitar
  - Mountain biking
  - Ballroom dancing

Outline

- Background
  - Transverse Jets
  - Problem Statement
  - Non-Dimensional Parameters
  - Design Space
- Apparatus
  - Water Flow Loop
  - Test Section Parts
- Flow Measurement
  - LDV
  - PLIF
- Results
  - Holdeman Scaling
  - Unmixedness



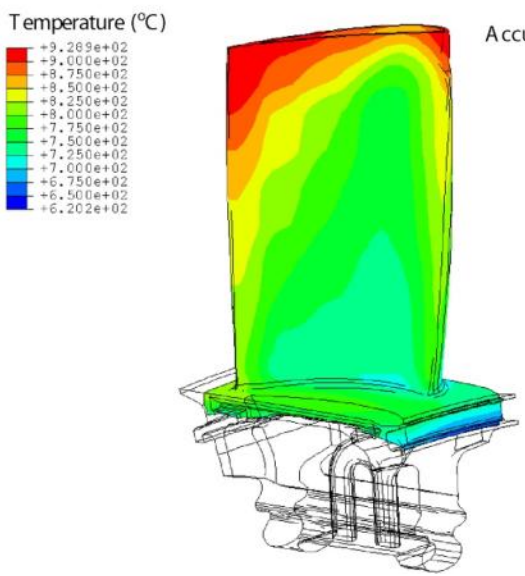
Introduction

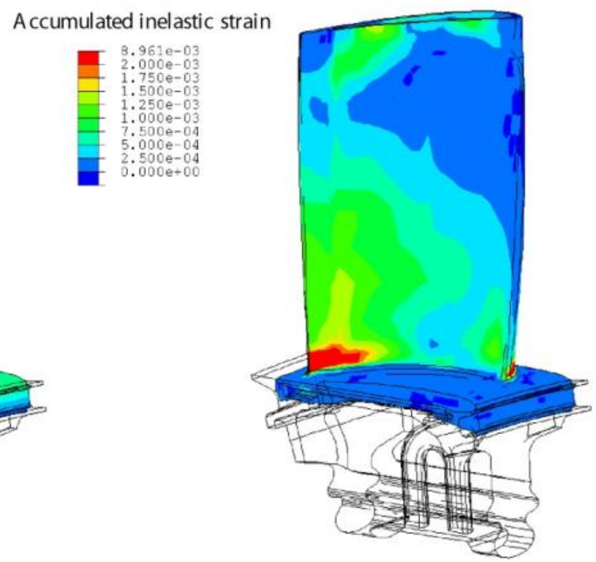
Background

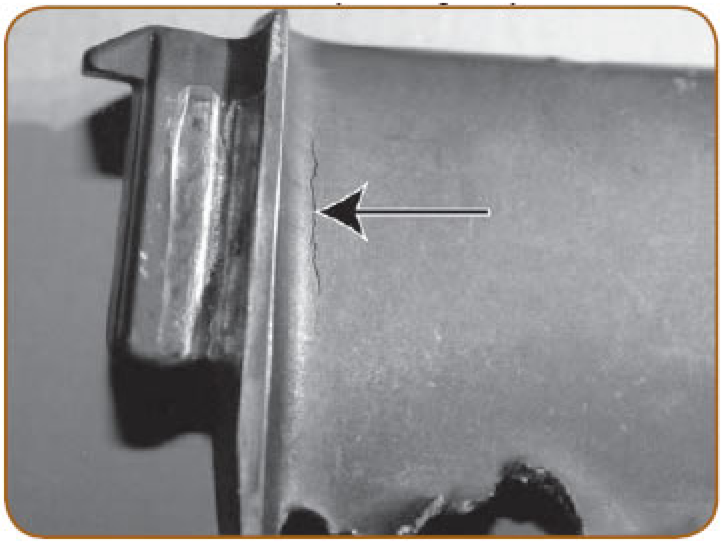
- Transverse jets (jets-in-crossflow) have been studied extensively in academia and industry
- Applications:
  - Smokestack dispersion
  - Gas turbine burners
  - VTOL Aircraft
- Use is well established in mixing of two dissimilar fluids for combustion devices
- Certain regimes of multiple jets have not been studied and are currently of interest to Air Force research goals

Problem Statement

- AF seeking to develop reusable high-performance liquid rocket engine
- Hindrances to reusability are turbine cycle fatigue and oxygen compatibility
- Turbine cycle fatigue issues
  - Density
  - Species
  - Temperature







Project Objective

- Investigate mixing behavior of multiple confined JICF to determine local optima
- Control parameters include velocity ratio, diameter ratio and number of jets
- Non-dimensional (ND) parameters of interest for scaling include momentum flux ratio, momentum ratio and others

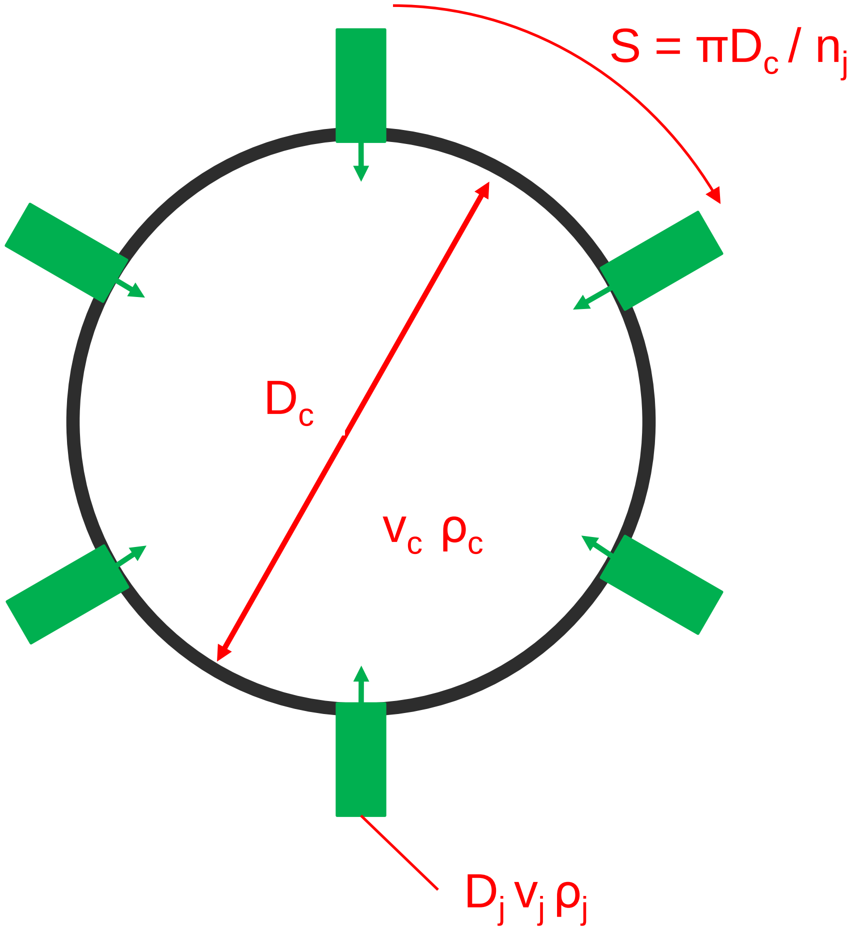
Confined Jet Configuration

- Studies have historically focused on gas turbine applications involving rectangular ducts or free jets
- Holdeman et al. studied 8-12 cylindrical orifaces in a confined can
- Downstream profiles similar when scaled with orifice spacing (S/D_c) and the square root of the momentum flux ratio

$$C = \left(\frac{S}{D_c}\right)\sqrt{J}$$

- For most cases, $C \approx 2.5$ (empirical)
- The optimum momentum flux ratio can then be given by:

$$J_{opt} = \frac{1}{2}\left(\frac{C n_j}{\pi}\right)^2$$



Momentum Flux Ratio: $J = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2$

Unmixedness

- Gas turbine combustors commonly use temperature as a means of analogizing concentration since they are both scalar quantities. The non-dimensional temperature can be defined as:

$$\theta = \frac{T_m - T}{T_m - T_j}$$

- Using optical techniques, concentration can instead be analogized by light intensity (non-intrusive)
- Spatial unmixedness can then be defined from the variance and normalized:

$$U = \frac{\frac{1}{m}\sum_{i=1}^{m}(C_i - \bar{C})^2}{\bar{C}^2}$$

Where m is the pixel count and C is concentration determined from calibration data and field corrections

Image Credit: Nova Lasers

Relevant Ratios

- Density Ratio $$\pi_1 = \frac{\rho_j}{\rho_c}$$ ← Not a priority in water flow experiment
- Velocity Ratio
  - Velocity of a single jet divided by crossflow $$\pi_2 = \frac{v_j}{v_c}$$
- Diameter Ratio
  - Diameter of a single jet divided by crossflow $$\pi_3 = \frac{d_j}{d_c}$$
- Number of Jets $$\pi_4 = n_j$$

Methodology

- Fix jet mass flow rates by cavitating venturis
- Adjust velocity ratio by changing core mass flow rate/core velocity for given geometry

$$\pi_2 = \frac{v_j}{v_c}$$

- Fix core diameter via standard test section
- Adjust jet diameters via interchangable inserts

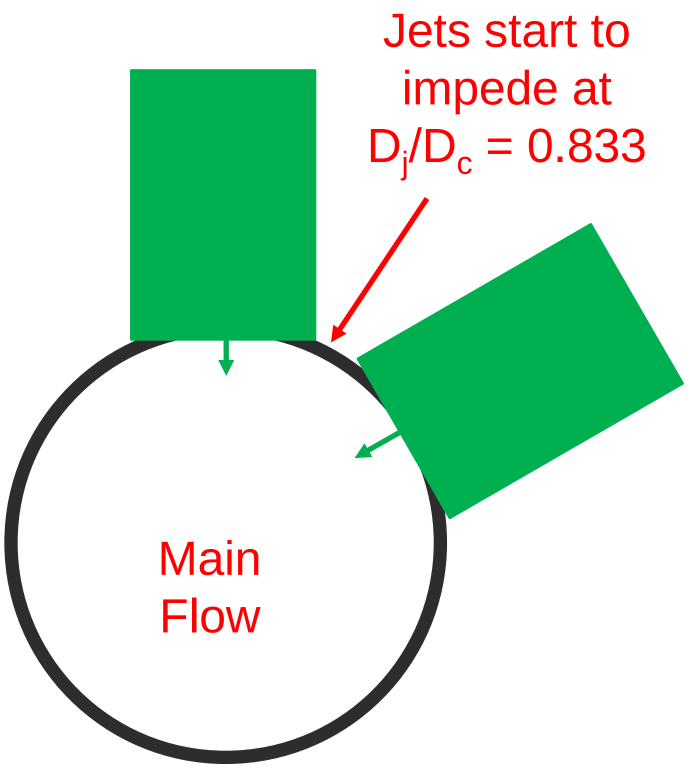
$$\pi_3 = \frac{d_j}{d_c}$$

- Maximum number of jets set by test section
- Use "blank" inserts to reduce the number of jets

$$\pi_4 = n_j$$

Design Space

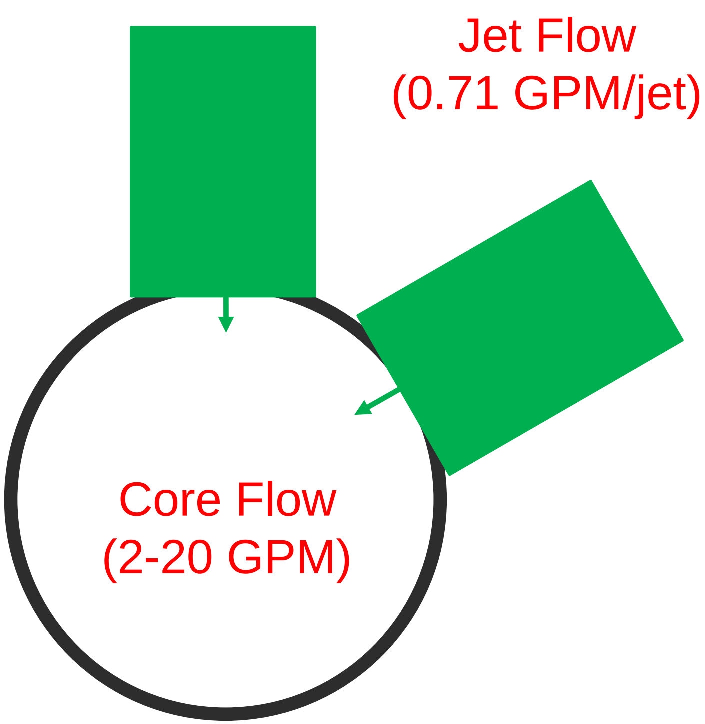
- How to determine relative ranges of velocity ratio, diameter ratio, and number of jets?
- Holdeman et al studied numbers of jets from 8-16
- Knowledge at lower n-values important for AF research goals
- 2, 3, 6 decided upon for symmetric injection
- Previous JICF work estimates diameter ratios between 0.1-0.3
- Used knowledge of pre-existing water flow facility to approximately size core diameter and jet diameters



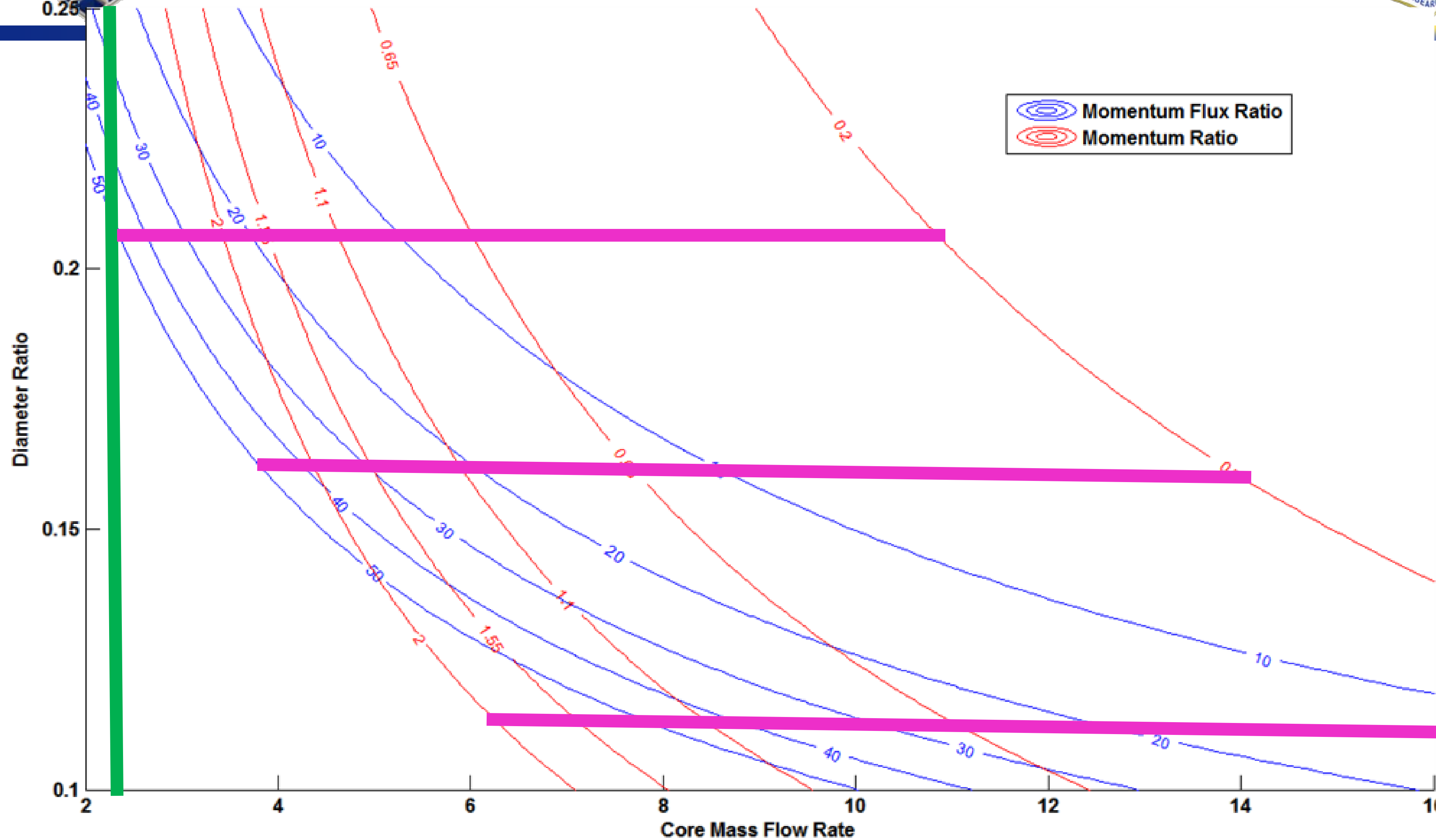
Design Space

- Previous JICF work studies J values from 5-200
- AF research focused on J ≈ 10-50
- Relevant velocity ratios set as square root of these values

- Previous JICF work estimates diameter ratios between 0.1-0.3
- Used knowledge of pre-existing water flow facility to approximately size core diameter and jet diameters
- Based on mass flow available, selected 0.12-0.21 as possible diameter ratios



Design Space



Facility Flow Rate Limit (~2.3 GPM)

Range of Investigation

Njets = 2

Design Space

$$\pi_2 = [\sqrt{10} \quad \sqrt{20} \quad \sqrt{30} \quad \sqrt{40} \quad \sqrt{50}]$$

$$\pi_3 = [0.12 \quad 0.165 \quad 0.21]$$

$$\pi_4 = [2 \quad 3 \quad 6]$$

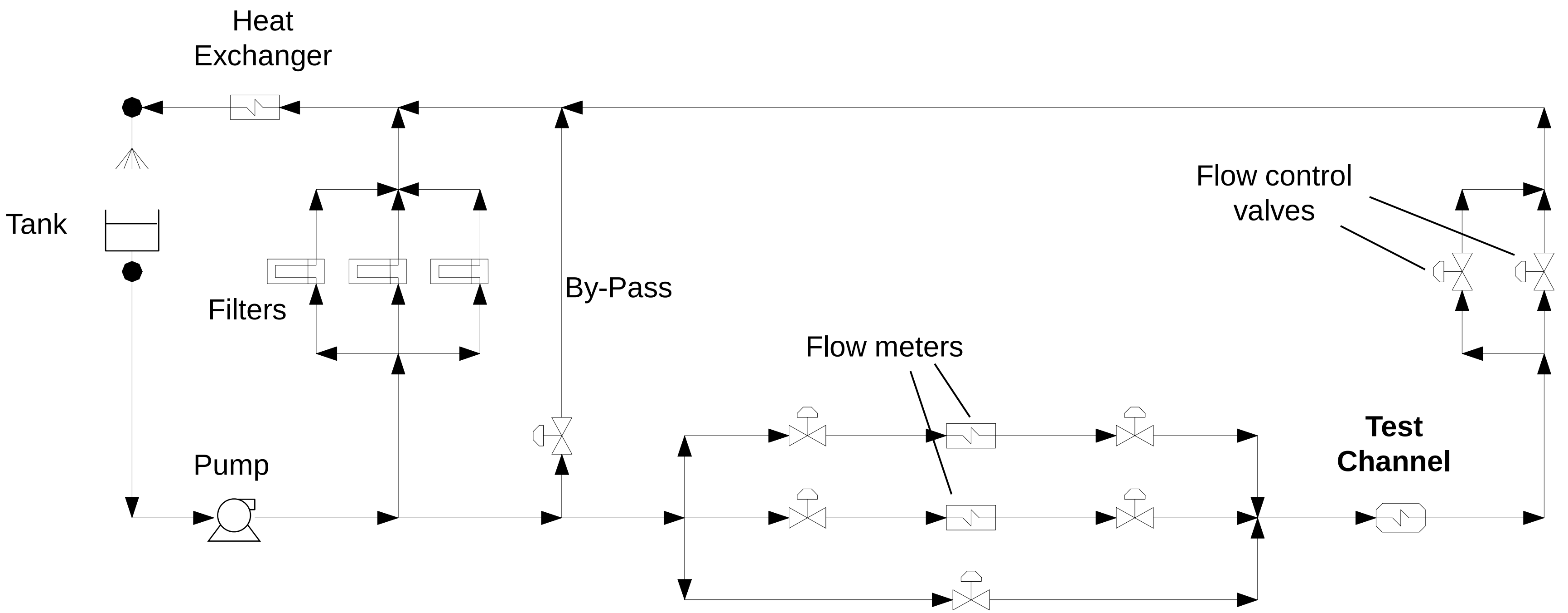
$$\boxed{5 \times 3 \times 3 = 45\ tests}$$

- Changing diameter ratio or number of jets requires hardware change
- Changing number of jets is slightly easier, since certain inserts will be left in place and others will be blocked off by using “blanks”
- Diameter ratio/number of jets assigned fewer values to minimize hardware changeover while still covering parameters of interest
- Velocity ratio easiest to change, assigned more test points in order to increase strength of correlations

Apparatus

Water Flow Loop

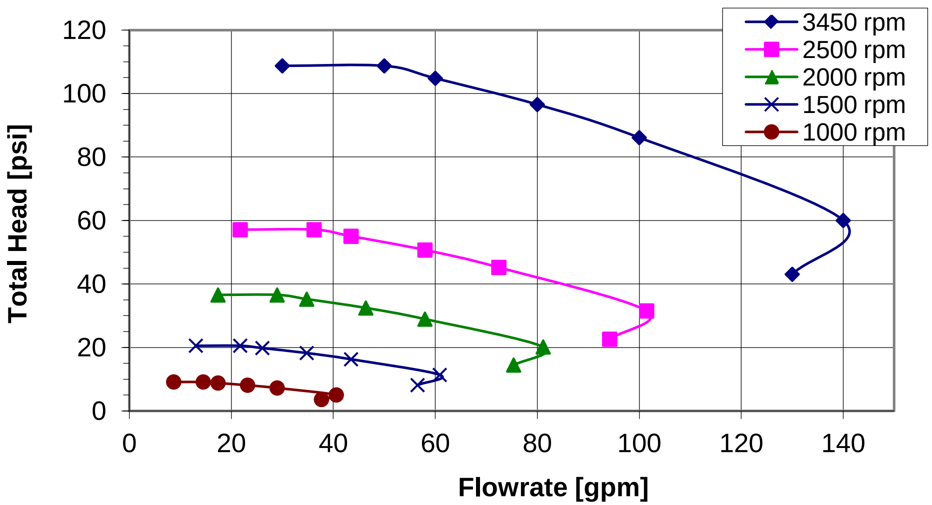
- Pre-existing hardware, being remodeled to accommodate JICF
- Recirculating loop, tank open to atm., manually operated
- Approx. capabilities: 100 psi discharge, 100 gpm, inlet temp 10 – 40 °C
- Good control of fluid temp, pressure & flow rate

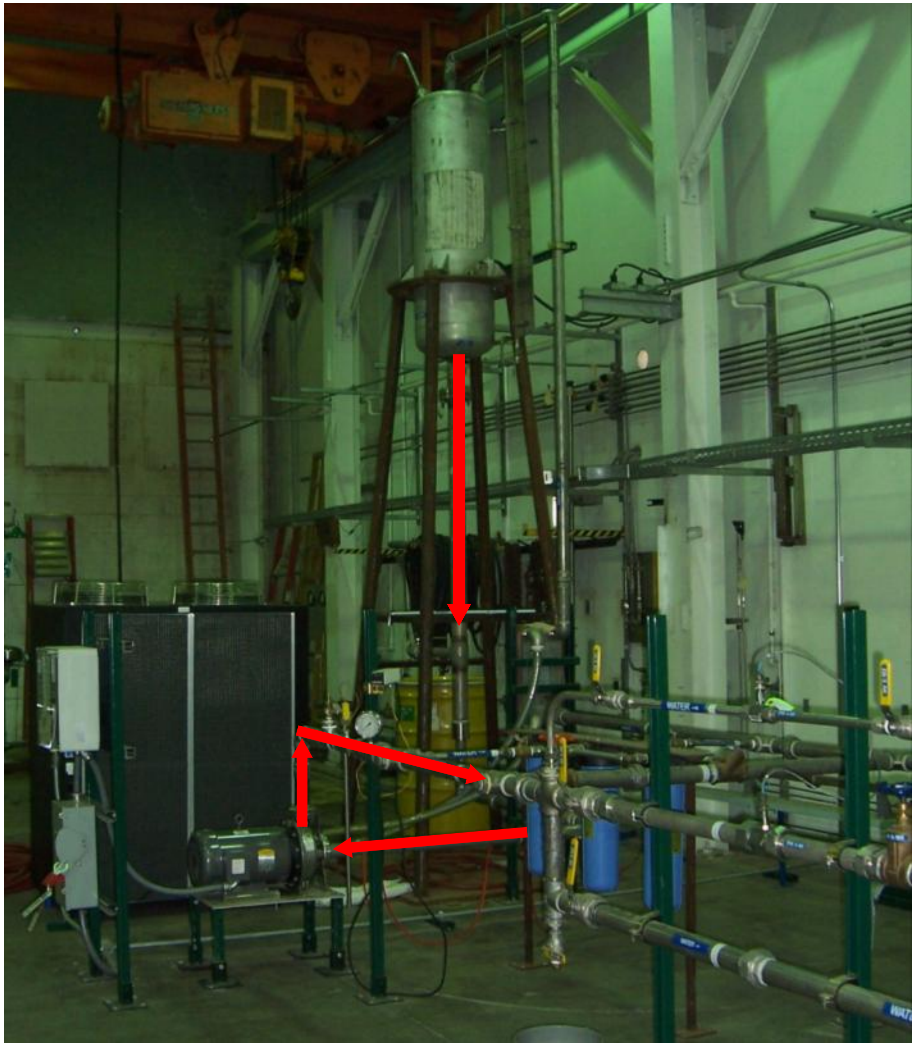


Water Flow Loop

- Water Tank
  - 60 gal cap
  - Open to atm
- Pump
  - Ebara A3U32-200
  - 10 hp (variable RPM)
  - Q @ 10-120 GPM
  - H @ 10-100 psi

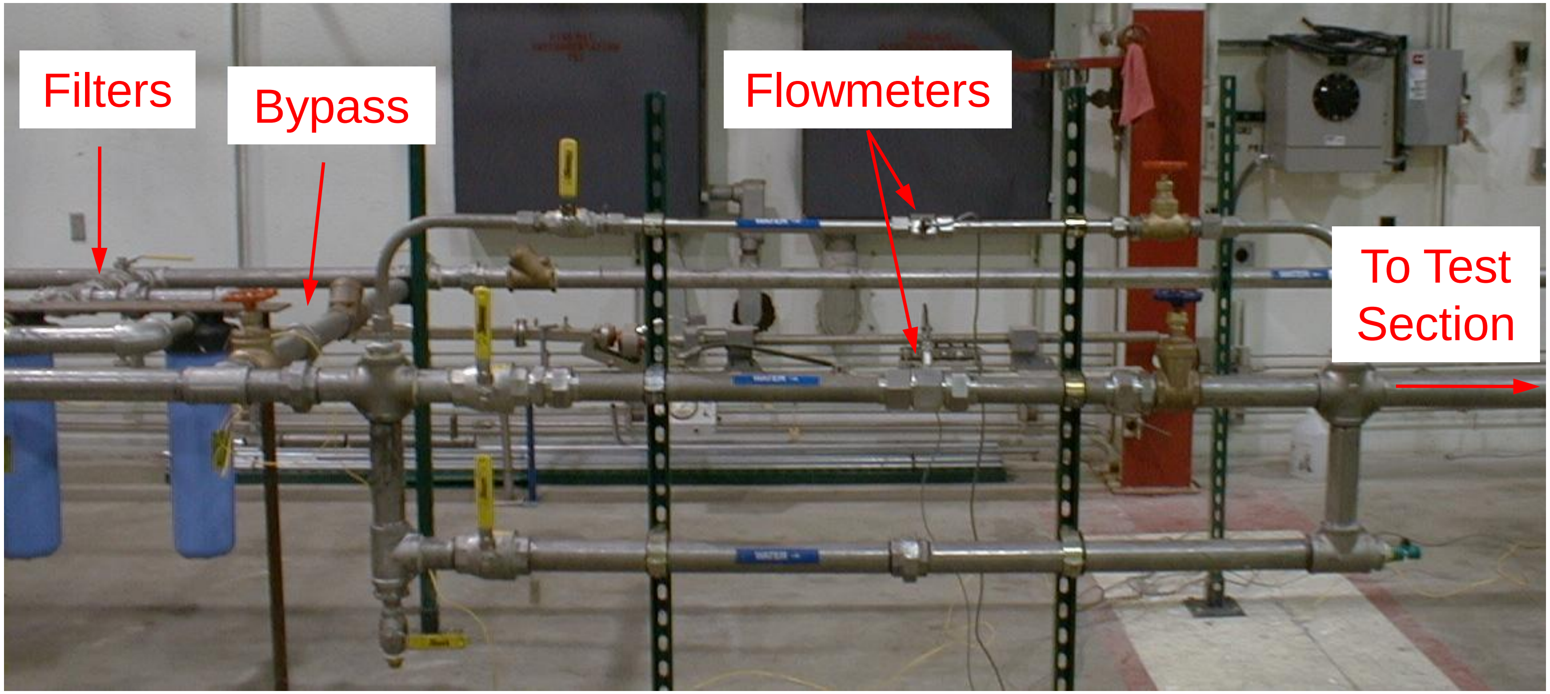
Operating Curves for Ebara Pump Model A3U32-200-10hp





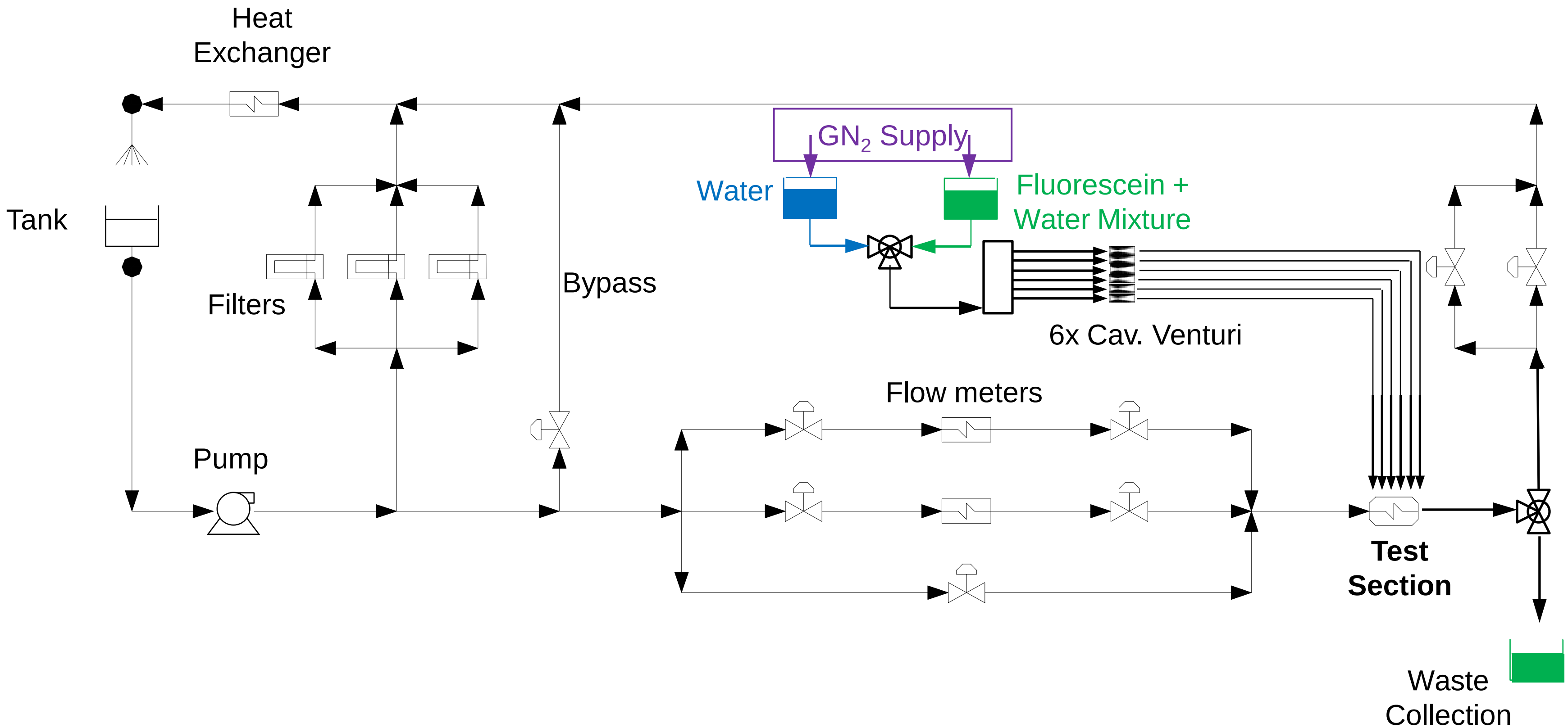
Water Flow Loop

- Line sizes (D = 1” or 2”) allows low or high Q operation while controlling velocity
- Using 1” line for most tests



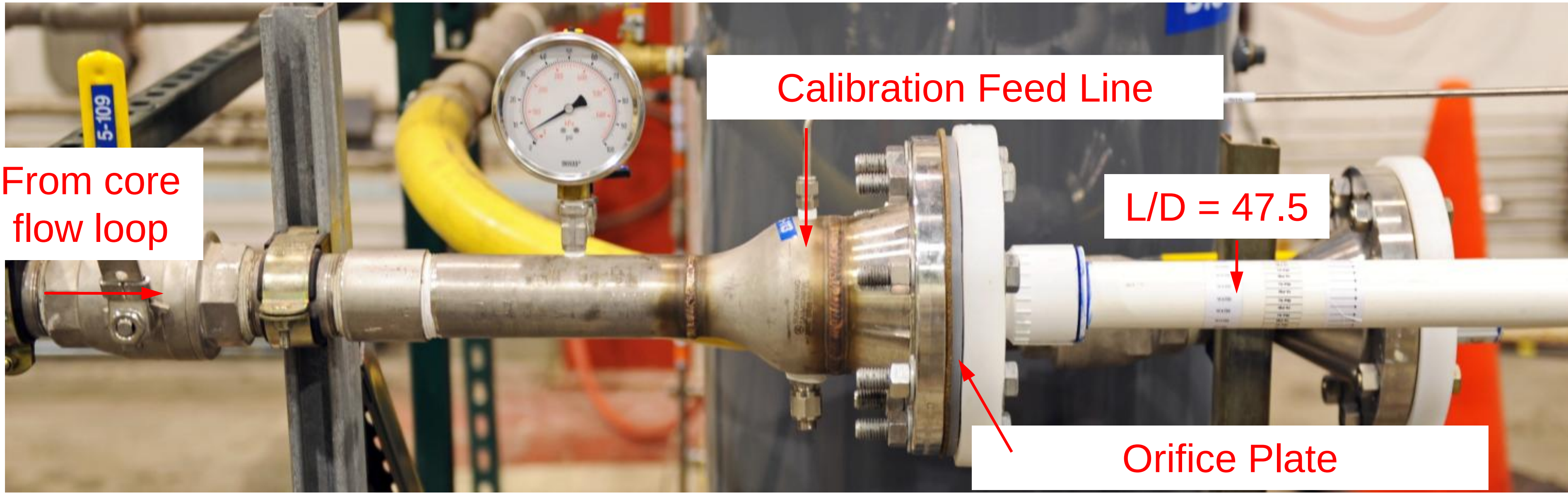
Modified Flow Loop

- Introduced injection piping
- Water used for shakedown/start-up
- Fluorescein used for data collection



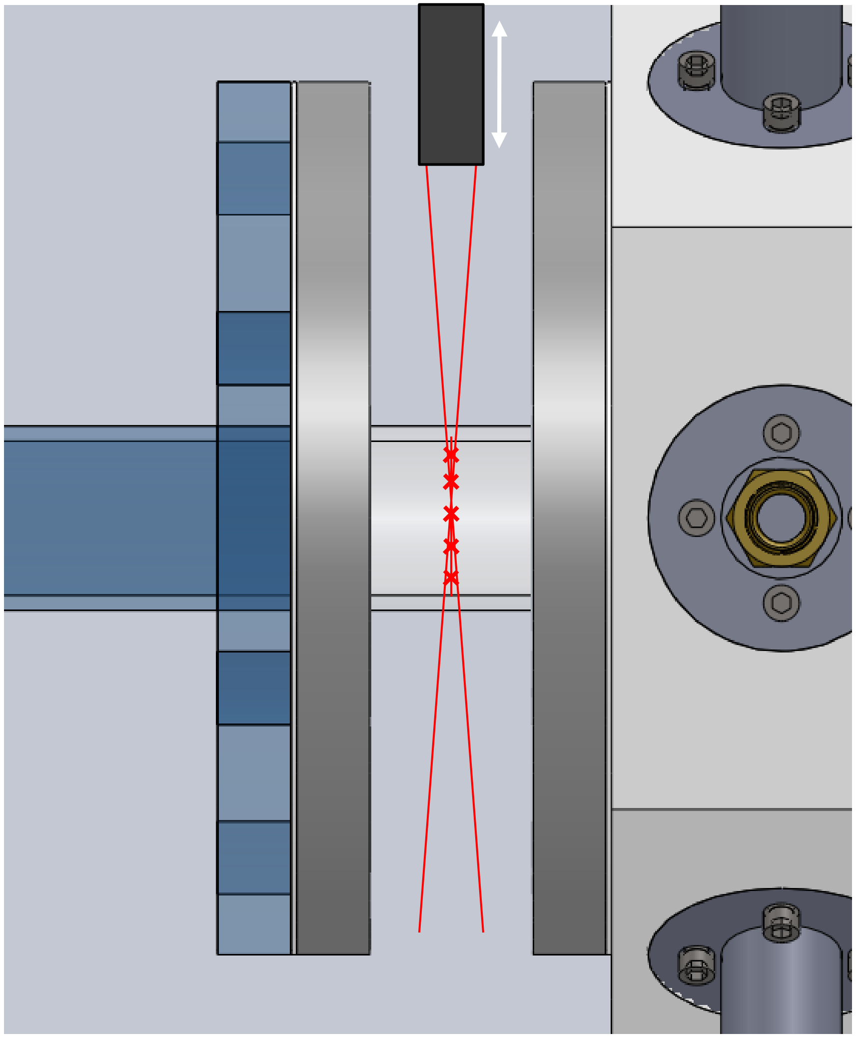
Turbulent Run-Up

- Orifice plate between inlet and turbulent run up to increase hydraulic resistance of the test section
- 1.5” PVC nominal



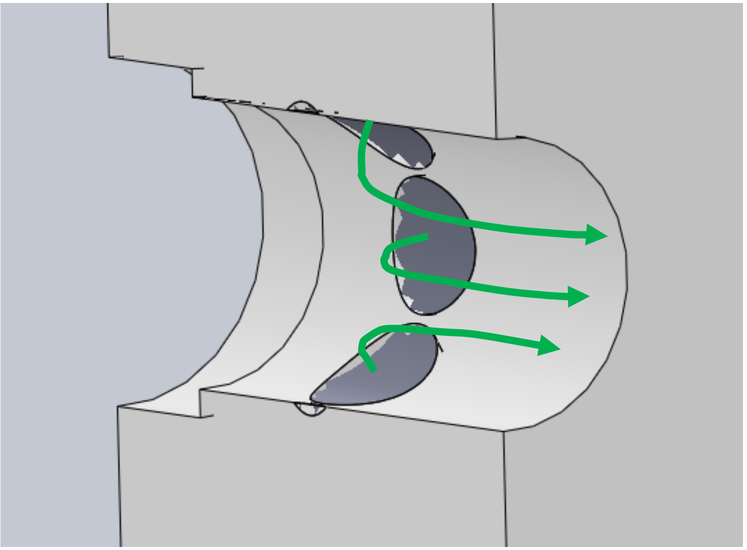
LDV Window

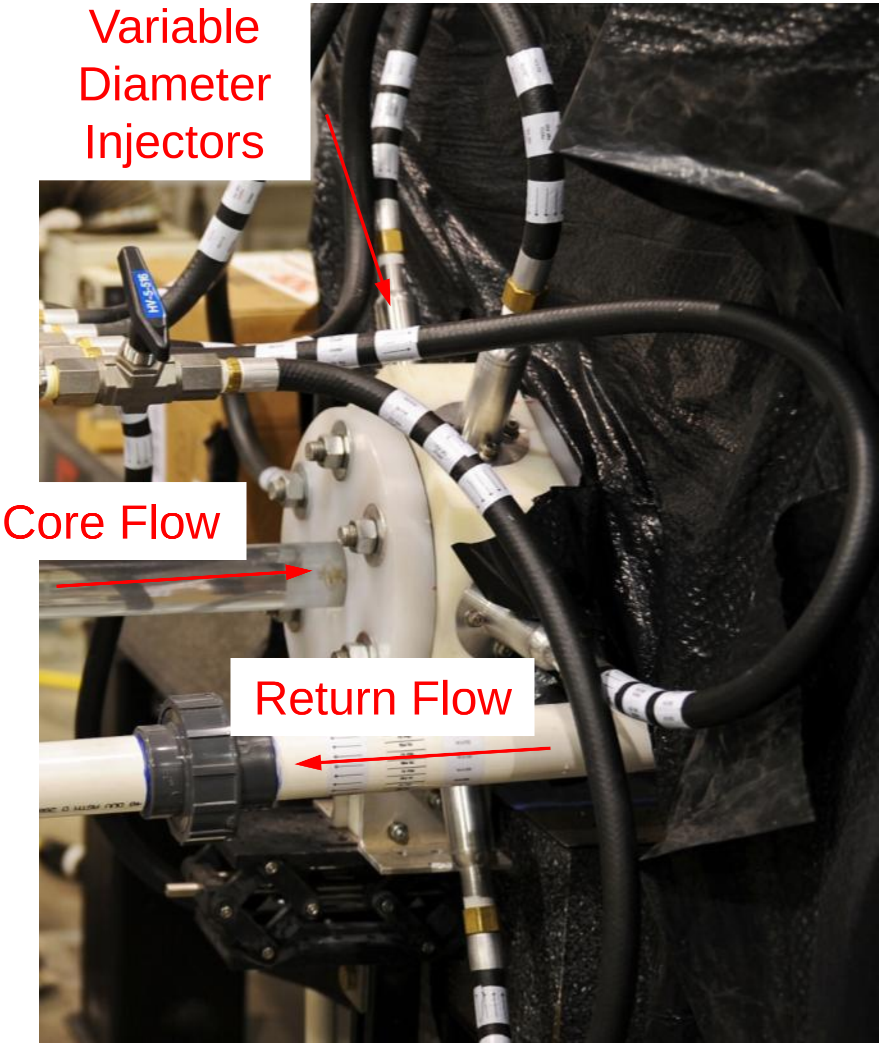
- Provides optical access before test section
- LDV crosshairs will traverse the window laterally to measure the inlet velocity profile (mean and turbulent fluctuations)
- Characterize for all potential core inflow velocities



Injection Block

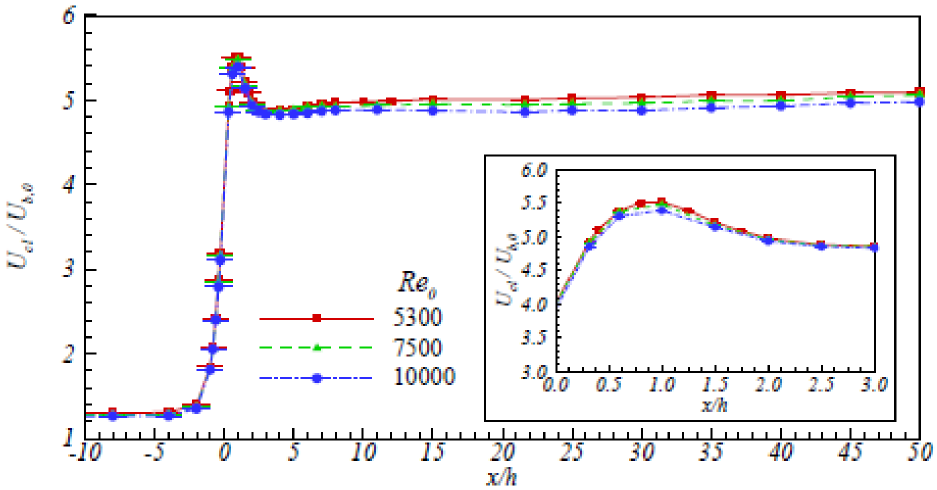
- Focal point of jets
- Nylon, machined on-site by AFRL techs
- Injection cross section is same as turbulent run-up (1.5” nominal)



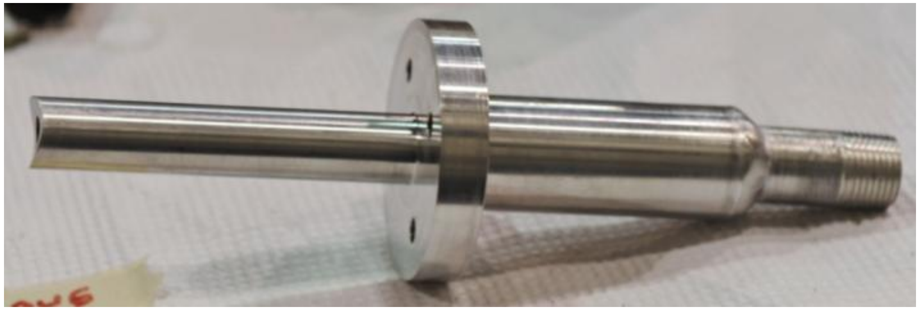


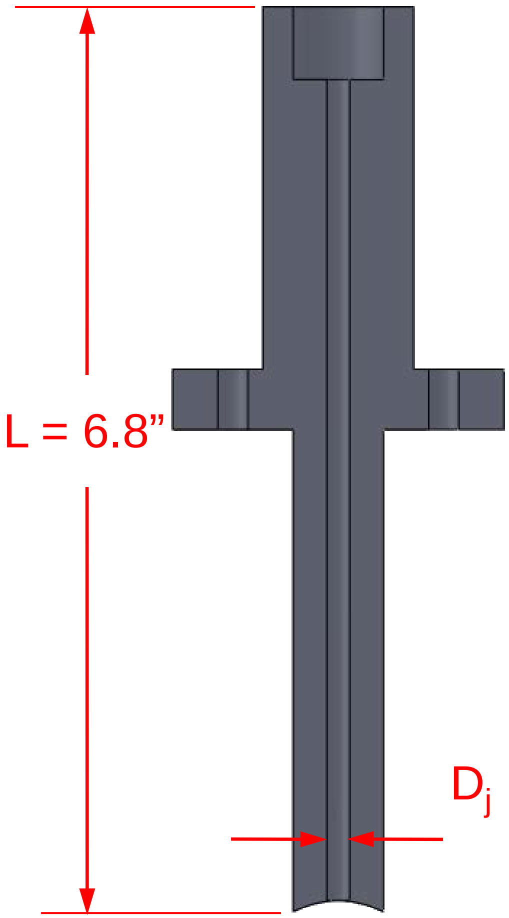
Jet Inserts

- All jet inserts machined the same for interchangability
- Characterize using LDV system
- Ajayi, Papadopoulos and Durst (1998) concluded that x/D ≈ 20 sufficient for velocity normalization (5300 < Re < 10000)



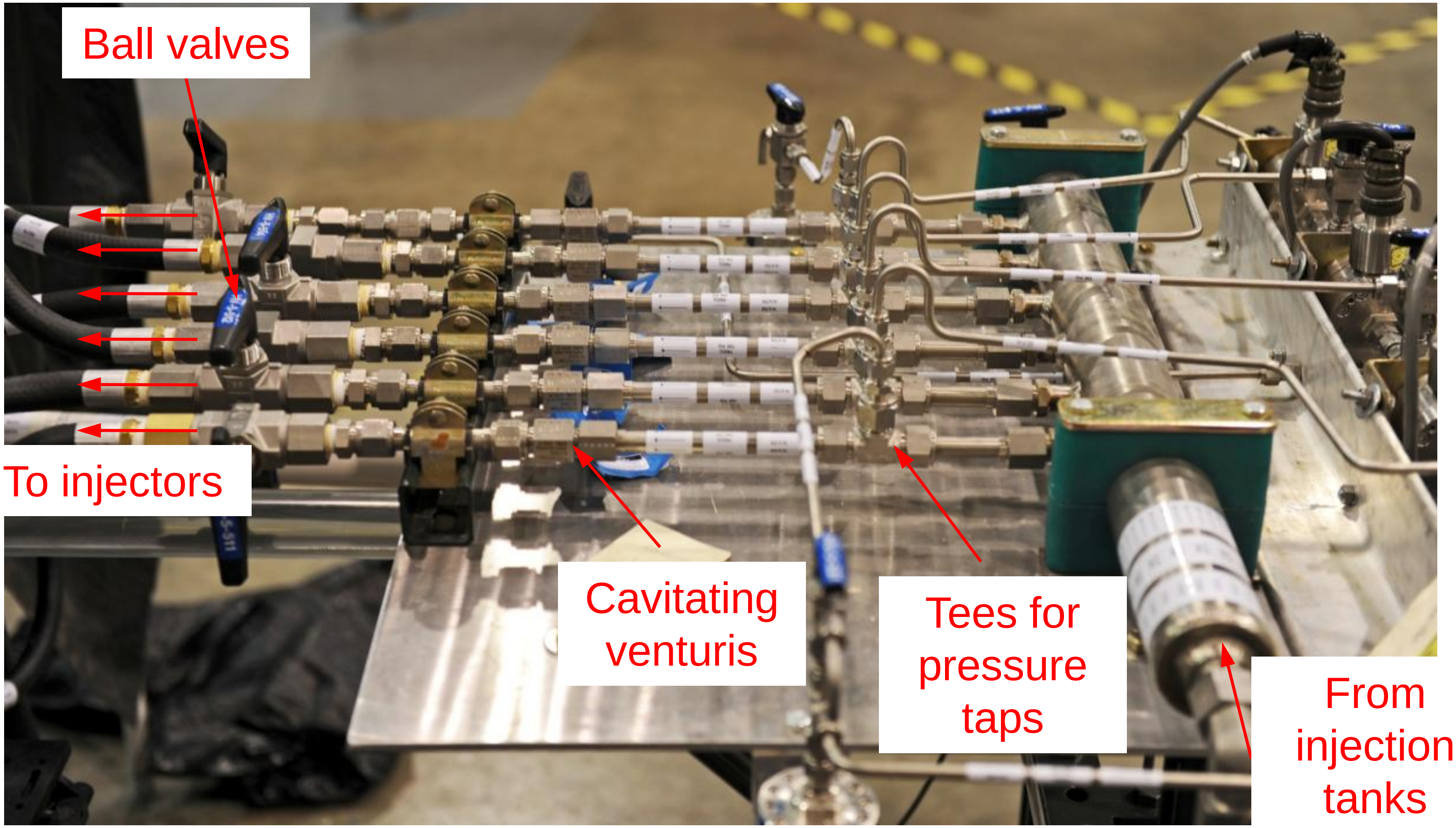
D_j/D_c	L/D_j	Re_j
0.12	35.6	10430
0.165	25.9	7590
0.21	20.3	5960



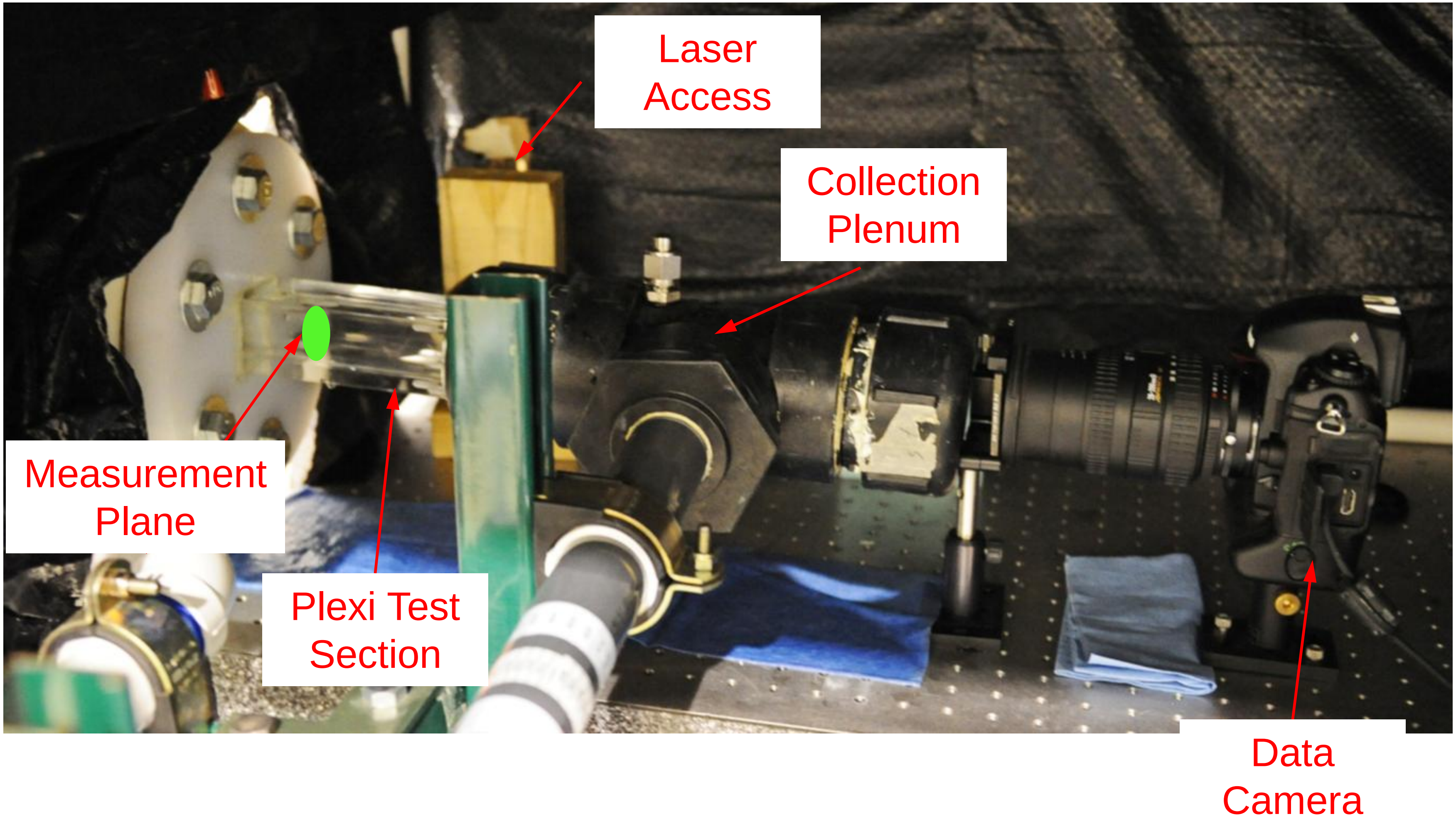


Injection Manifold

- Pressure drop across injection manifold is minimal
- Variation between lines is < 0.07 psi
- Resulting ΔQ between lines is < 1%



Measurement Window



Flow Measurement

miniLDV System

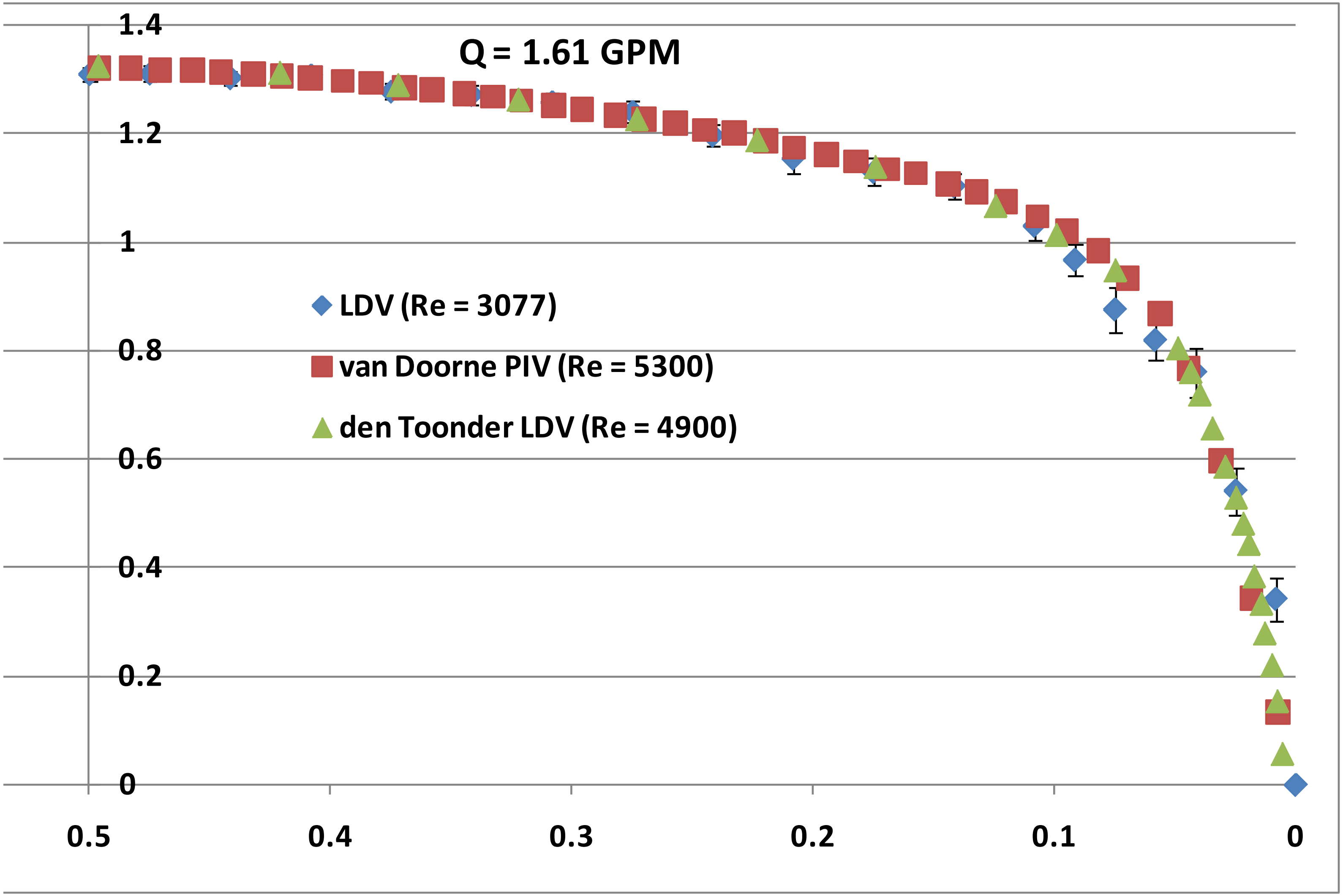
- Lenses, beam splitter, and photodetector housed in a single unit
- Powered by 60 mW diode laser (output power 44 mW)
- Measurement specs:
    - 1 mm/s – 300 m/s
    - Accuracy 99.7%
    - Delivers U and u’

Diode Laser

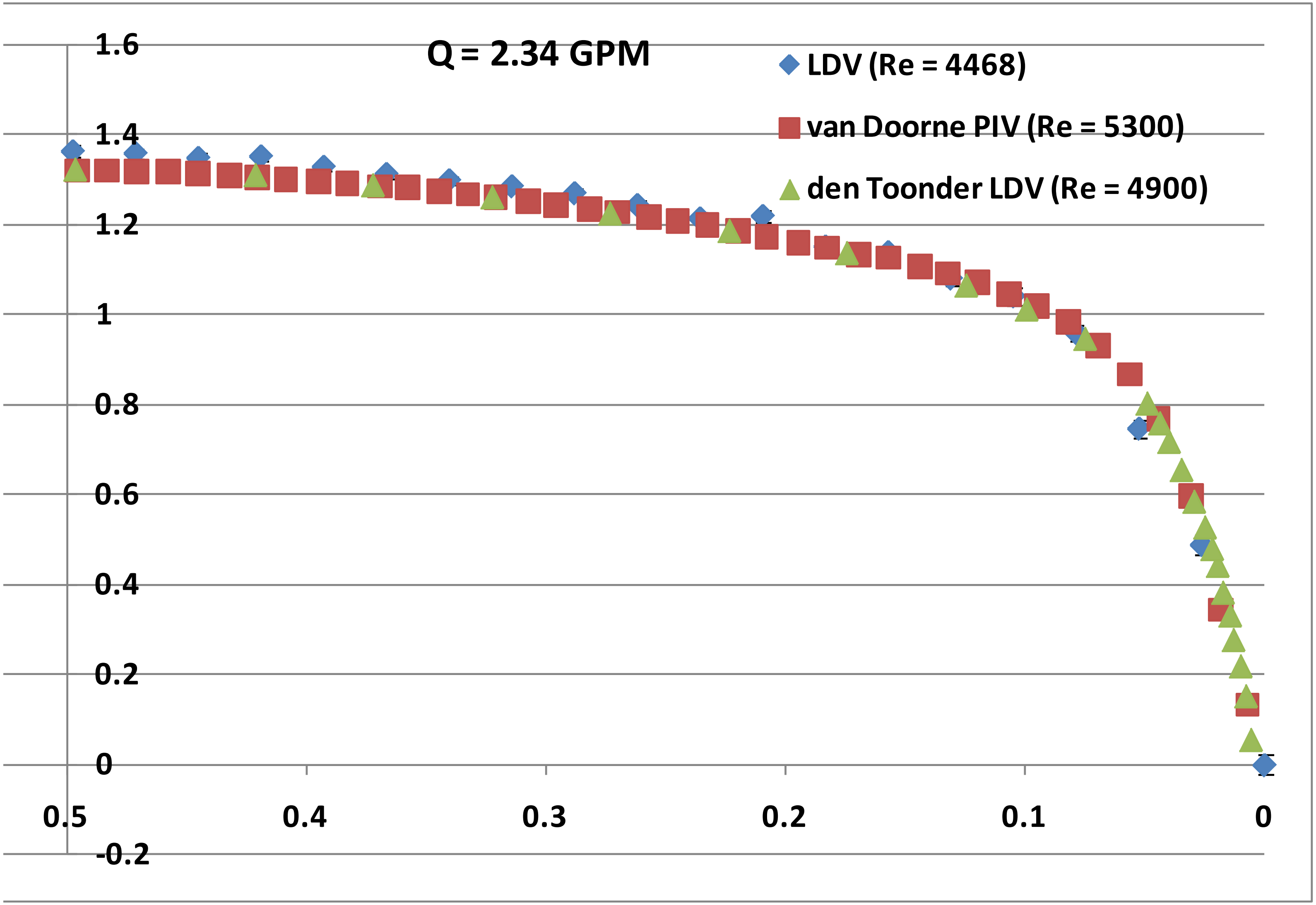
Bandpass Filter

Image Credit: Measurement Sciences

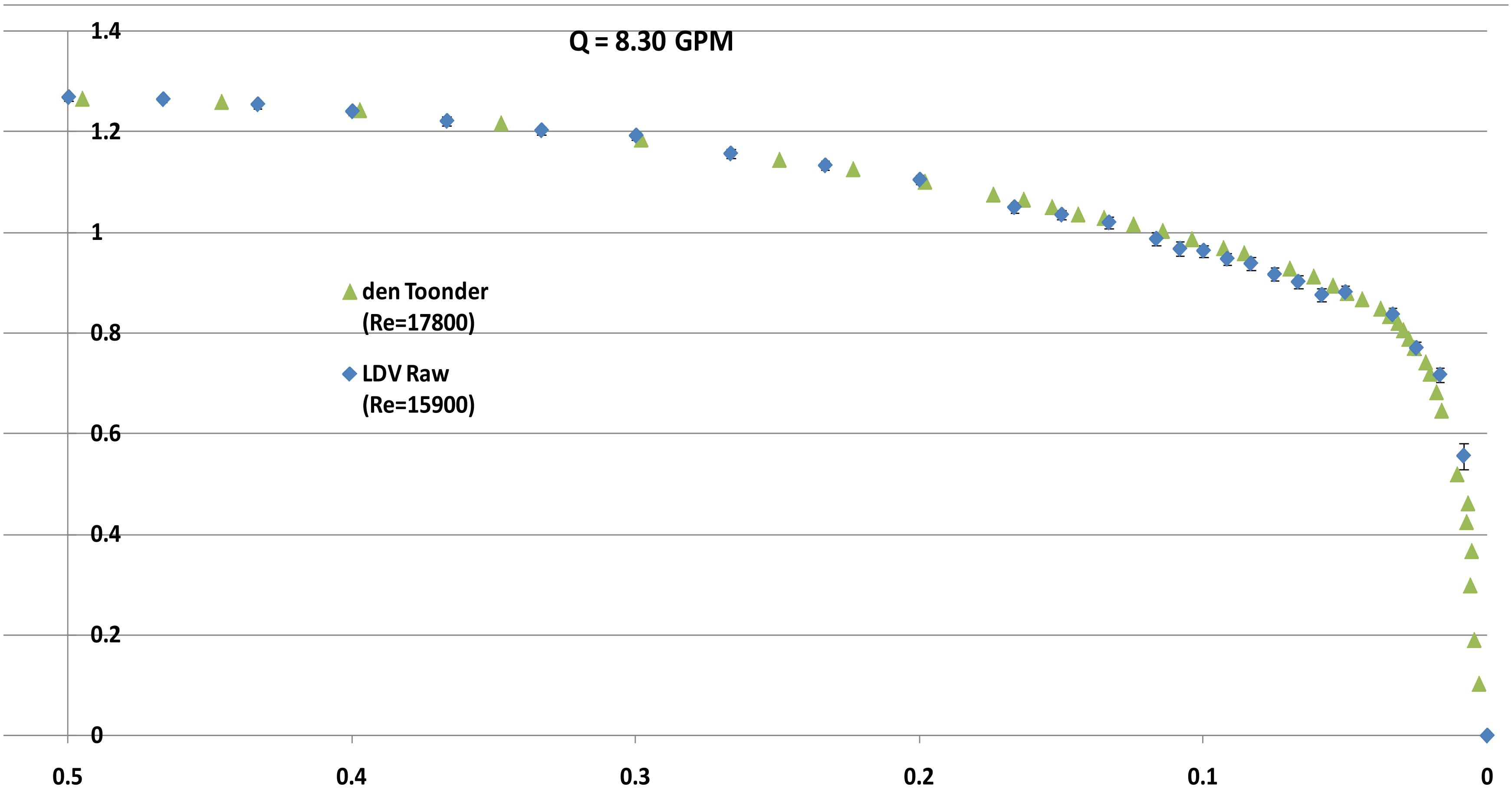
LDV Profiles



LDV Profiles



LDV Profiles



Planar Laser Induced Fluorescence

- Laser spread to a sheet using a cylindrical lens
- Laser energy excites fluorescent agent seeded into fluid of interest
- Calibrate using:
  - Laser Sheet Intensity
  - Injection fluid concentration
  - Exposure time

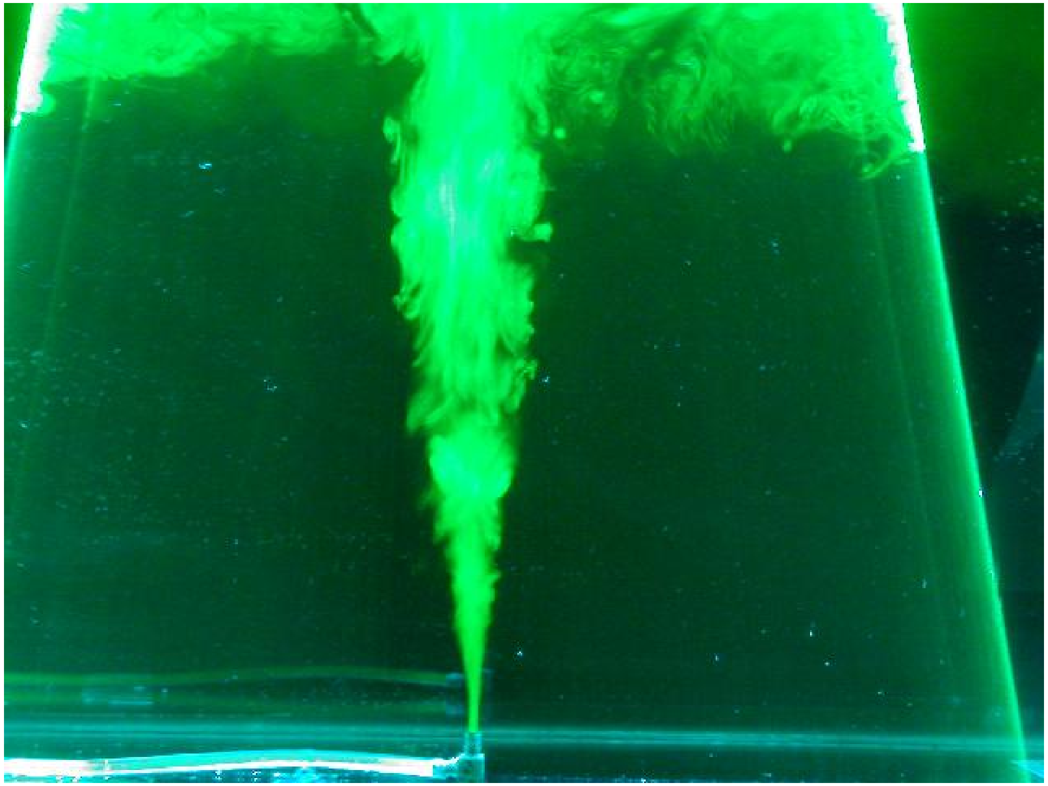


Image Credit: R. McLaughlin, University of North Carolina, Chapel Hill

Planar Laser Induced Fluorescence

- Fluorescent agent is sodium fluorescein ($C_{20}H_{10}Na_2O_5$)
- Benefits:
  - High quantum yield (~94%)
  - Water soluable
  - Relatively safe
- Other chemicals considered were Rhodamine (G and 6B); downselected for safety and ease of handling
- Absorption spectrum overlaps sufficiently with Ar-Ion laser @ 514 nm

Absorption Max	**~494 nm**
Emission Max	**~521 nm**

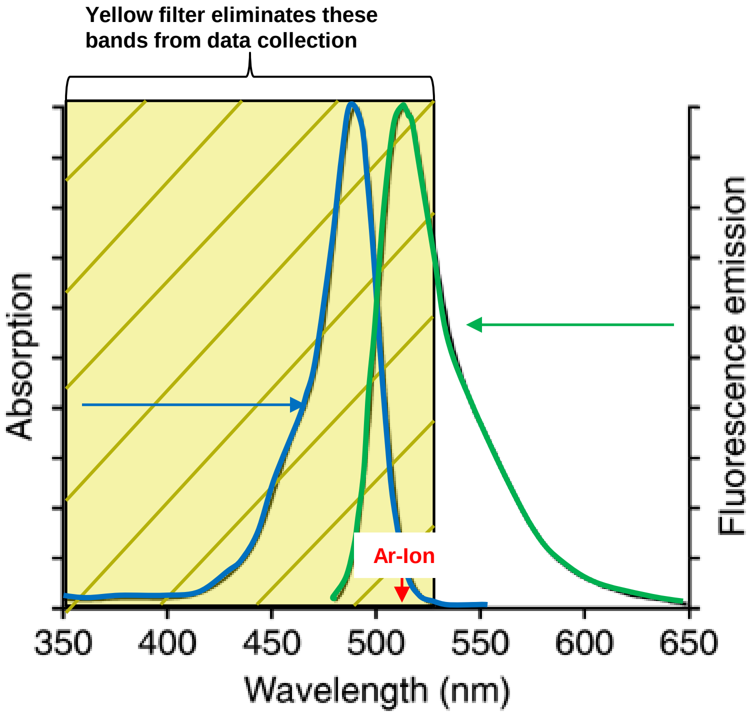
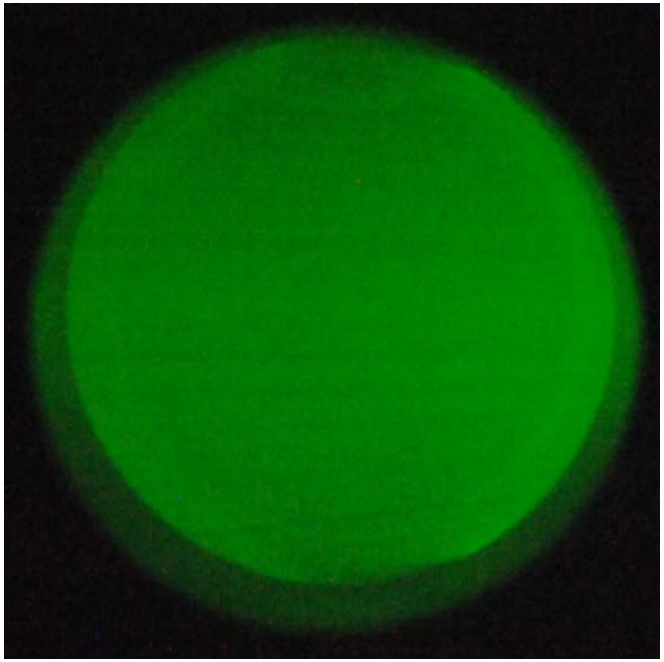


Image Credit: Invitrogen

In-Situ Calibration

- Raw field intensity
  - Data set taken per test
  - 3-4 images per test
- Dark field intensity
  - Taken before each test
  - Background correction for camera pixels
- Reference field intensity
  - Taken daily
  - Fluid-filled test section at pure jet fluid concentration
  - Accounts for attenuation, beam shape and other environmental factors

$$I_{NORM} = \frac{I_{RAW} - I_{DF}}{I_{REF} - I_{DF}}$$



Sample reference image
Highpass Filtered at 530 nm
C = 4.8×10^{-8} mol/L
f-stop = 11
Exp time = 2 sec

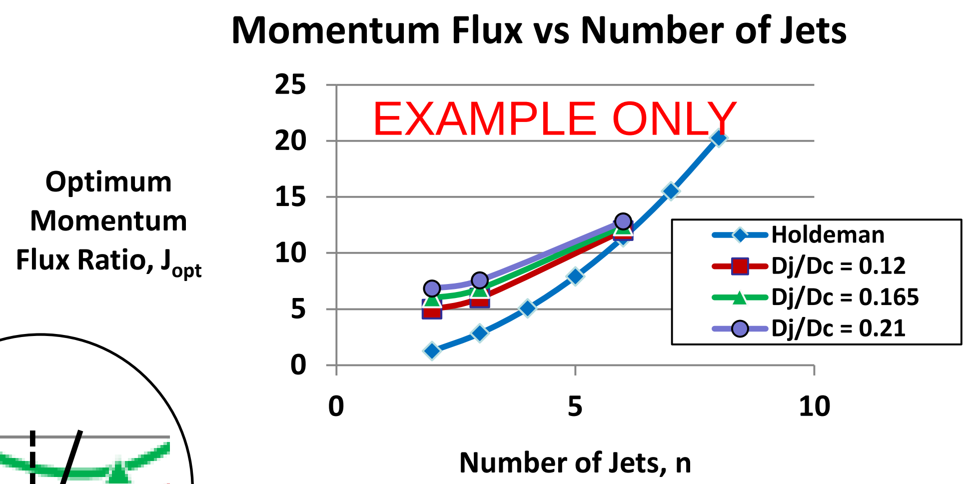
Results

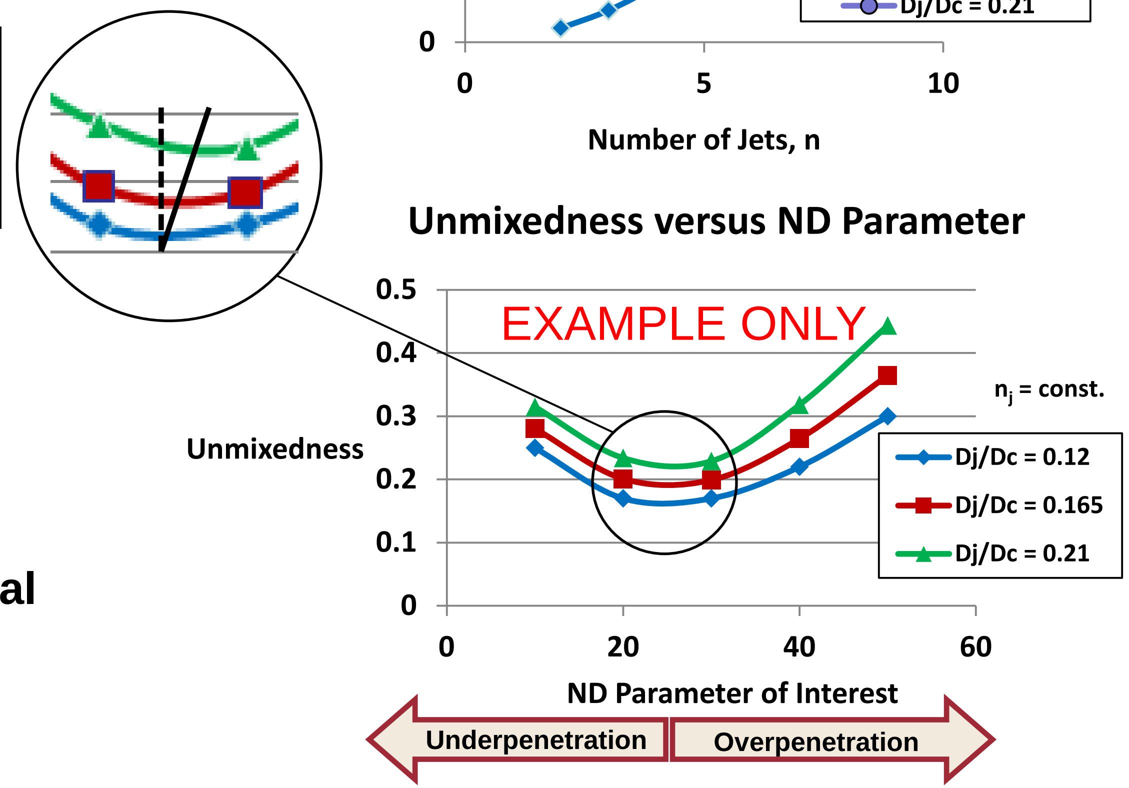
We’re not kidding!

Proposed Results

- **Holdeman deviation**
  - $n_j < n_{critical}$ (≈ 6)
  - $J_{opt} = \frac{1}{2}\left(\frac{C n_j}{\pi}\right)^2$

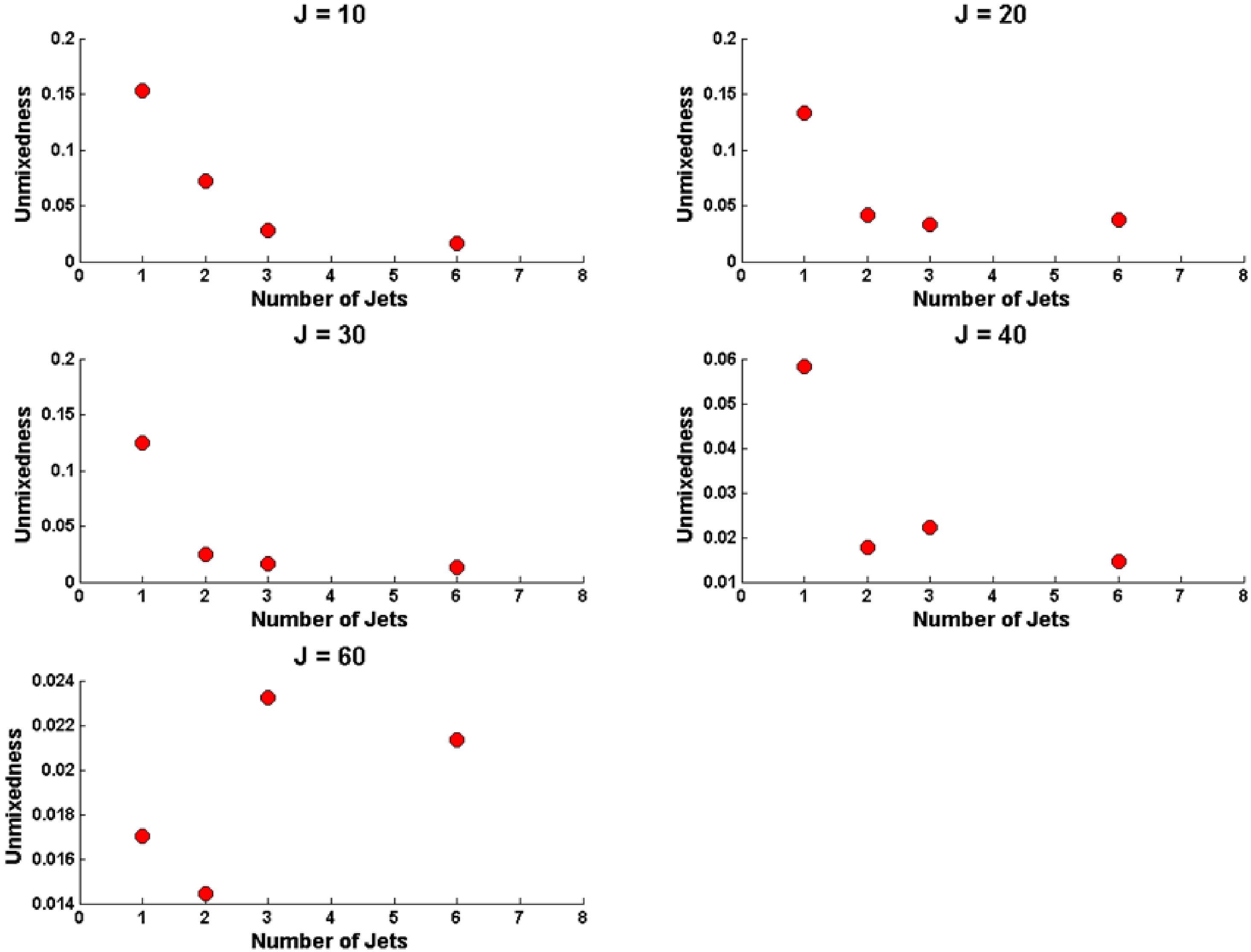
A change in the optimum unmixedness with the ND parameter of interest would indicate poor scaling



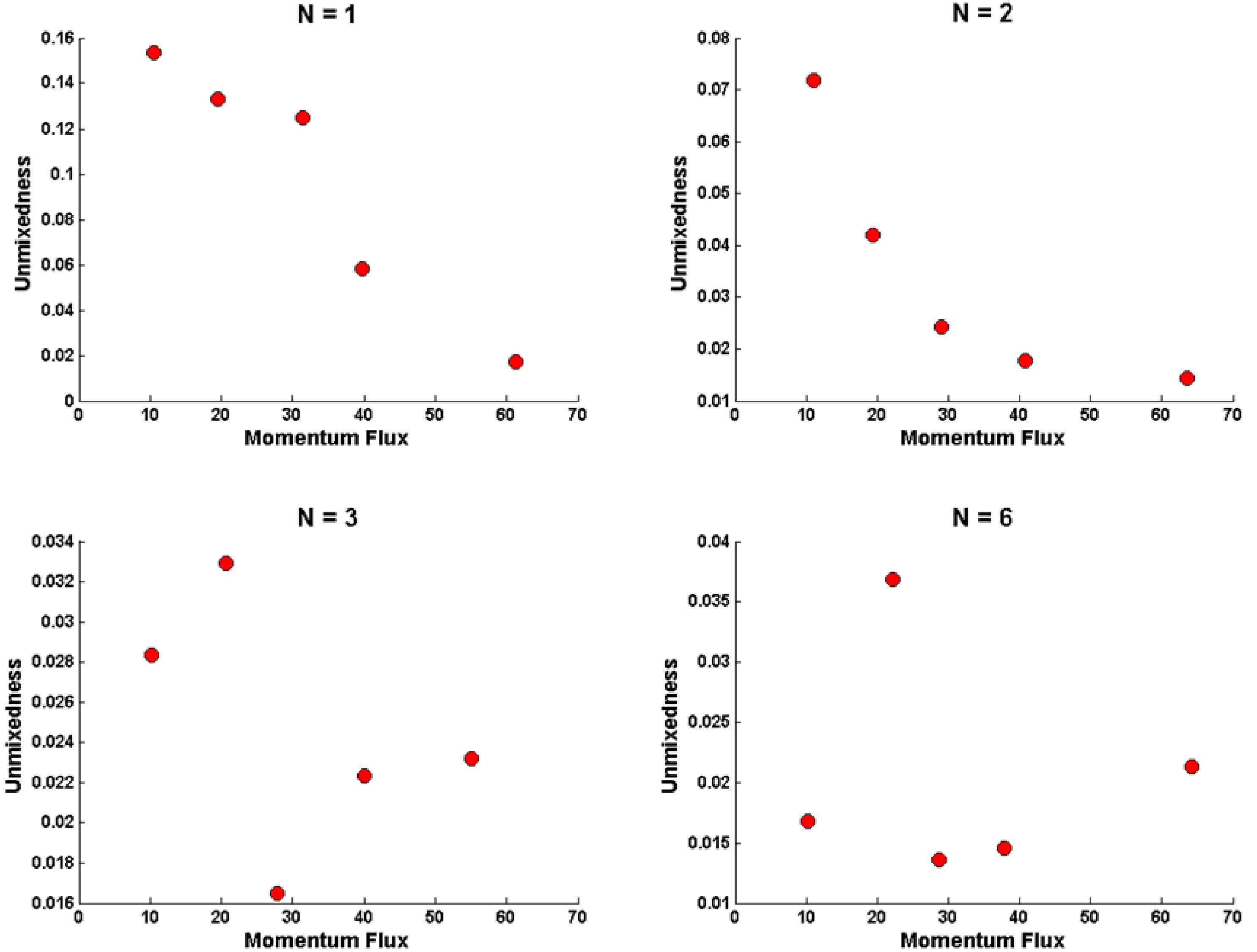


- **Show how unmixedness varies with ND parameters**
- **Concentration images**
- **Analysis of macro-level spatial flow features**

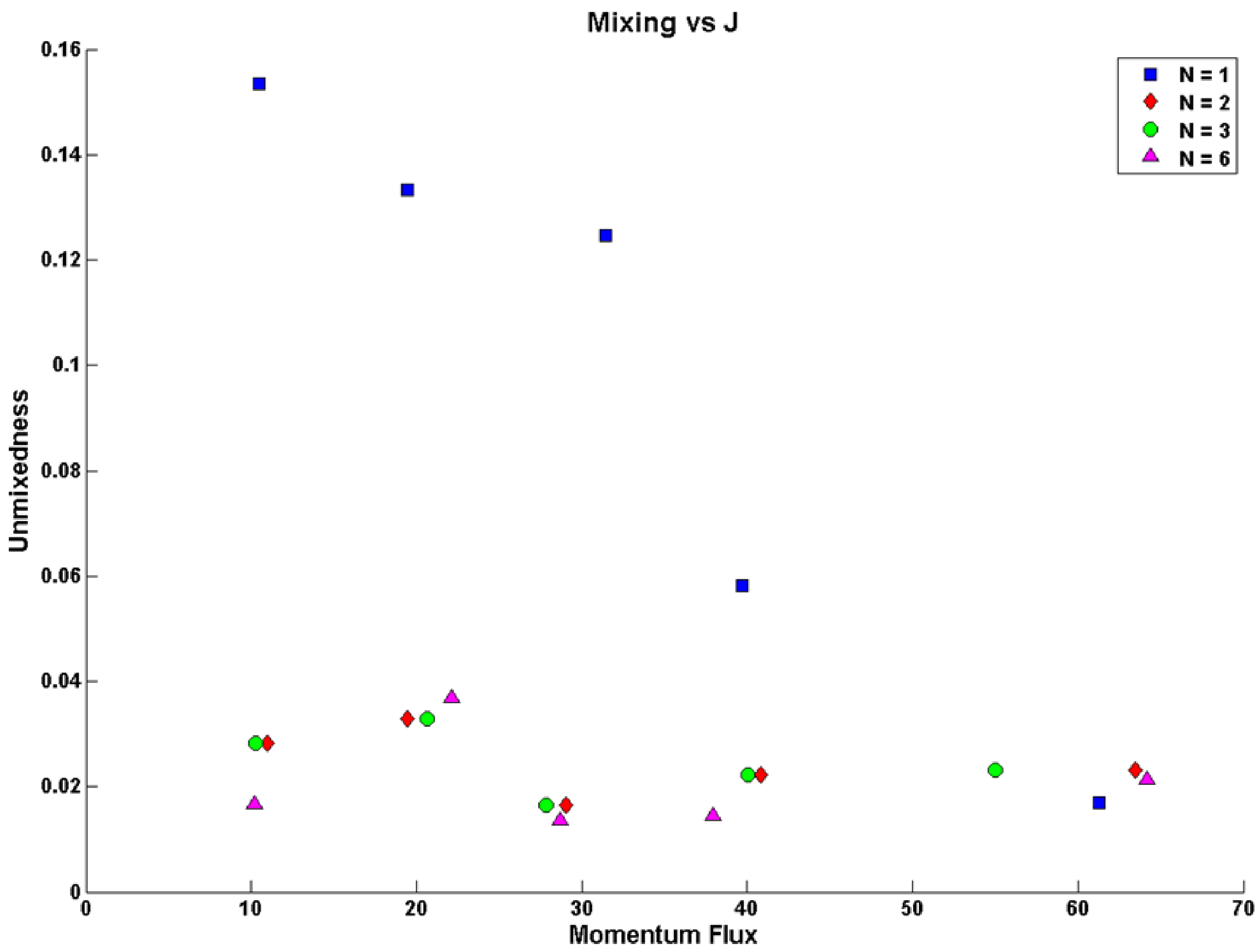
Unmixedness



Unmixedness



Unmixedness



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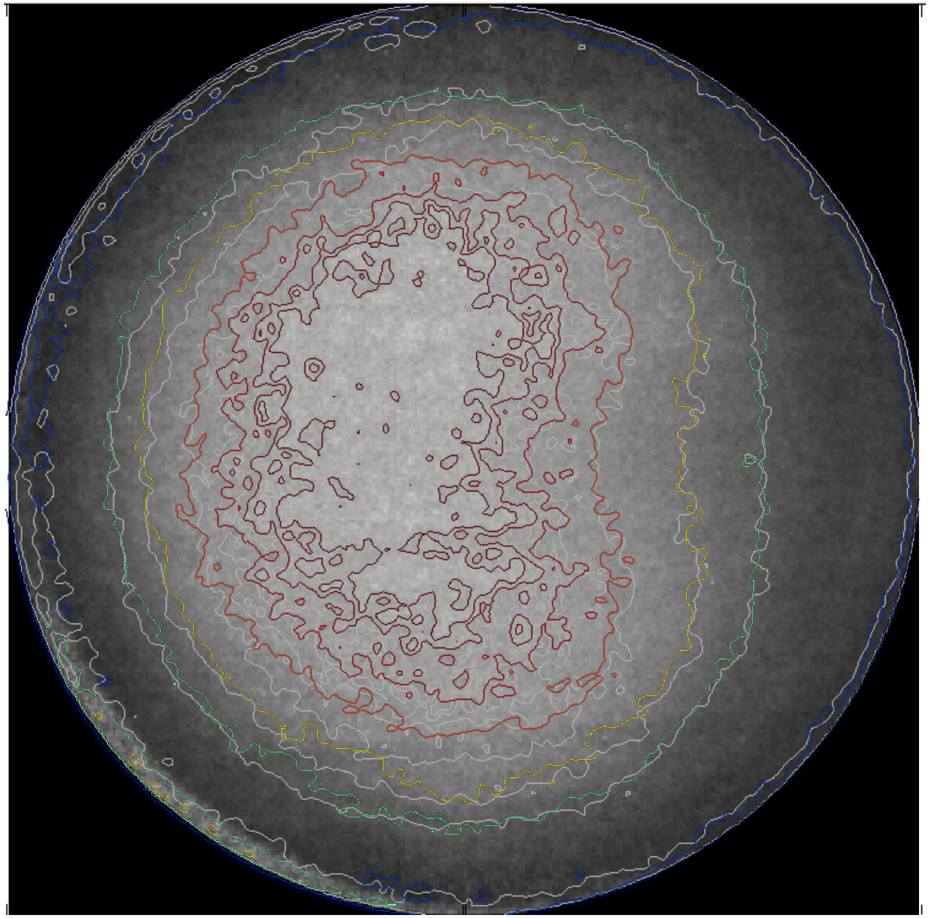
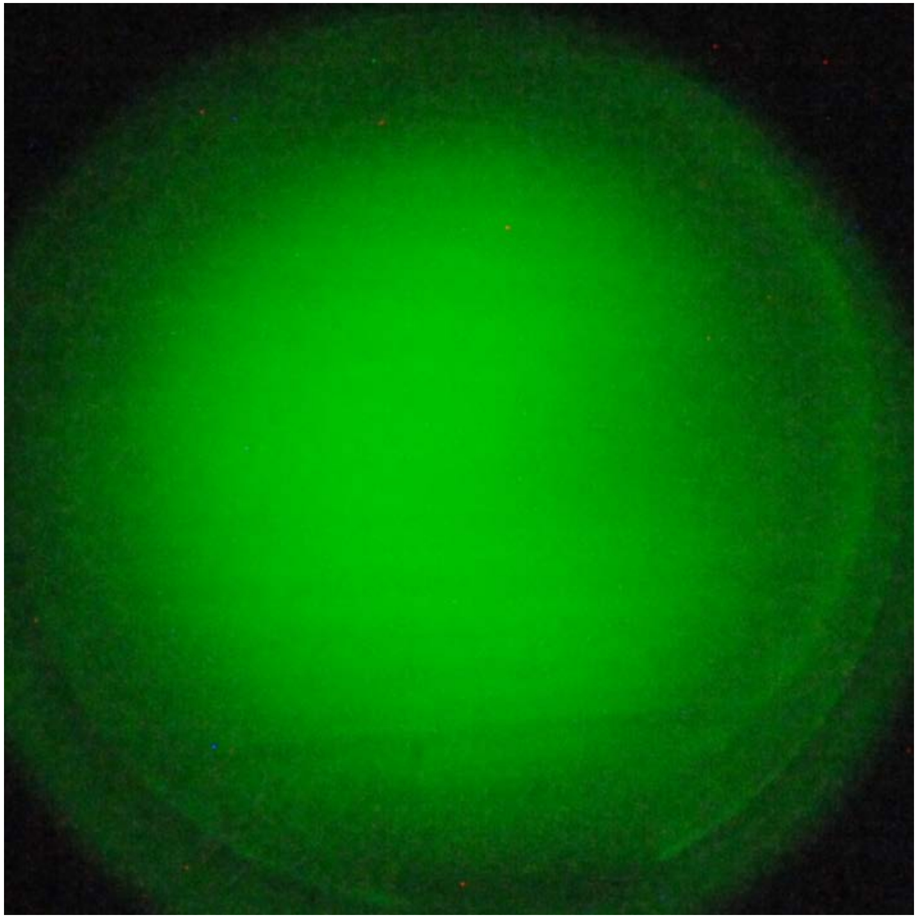
Sample Case – N1_J10_D12

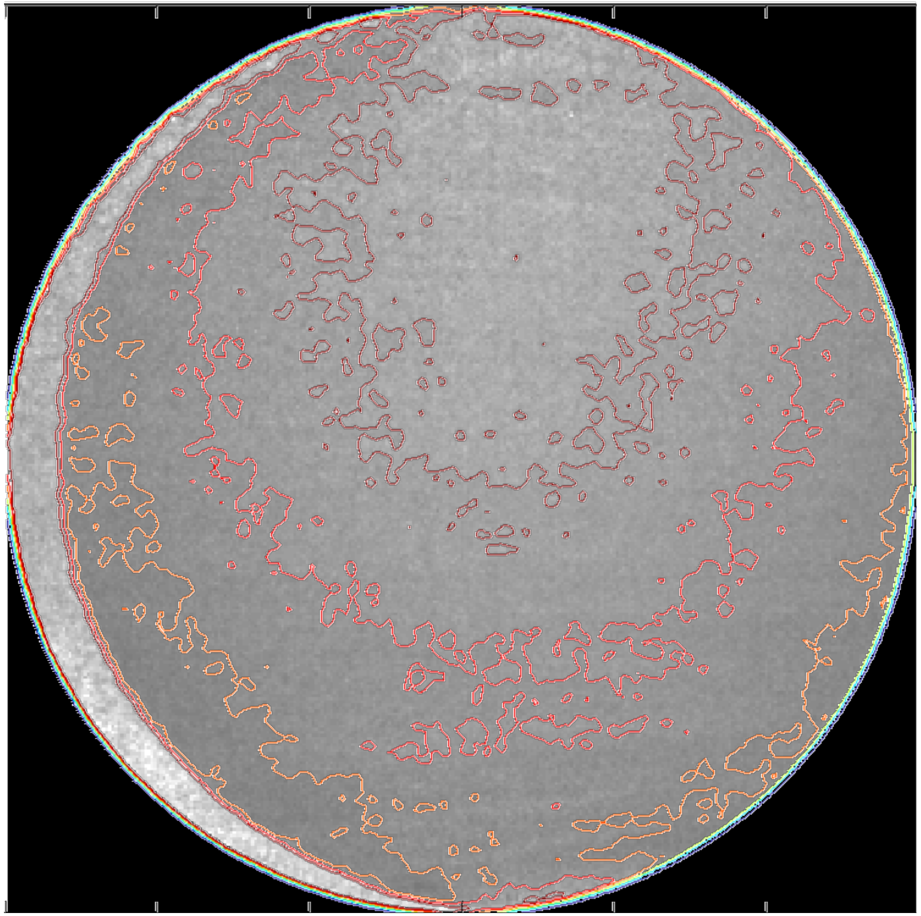


Processed image with contours

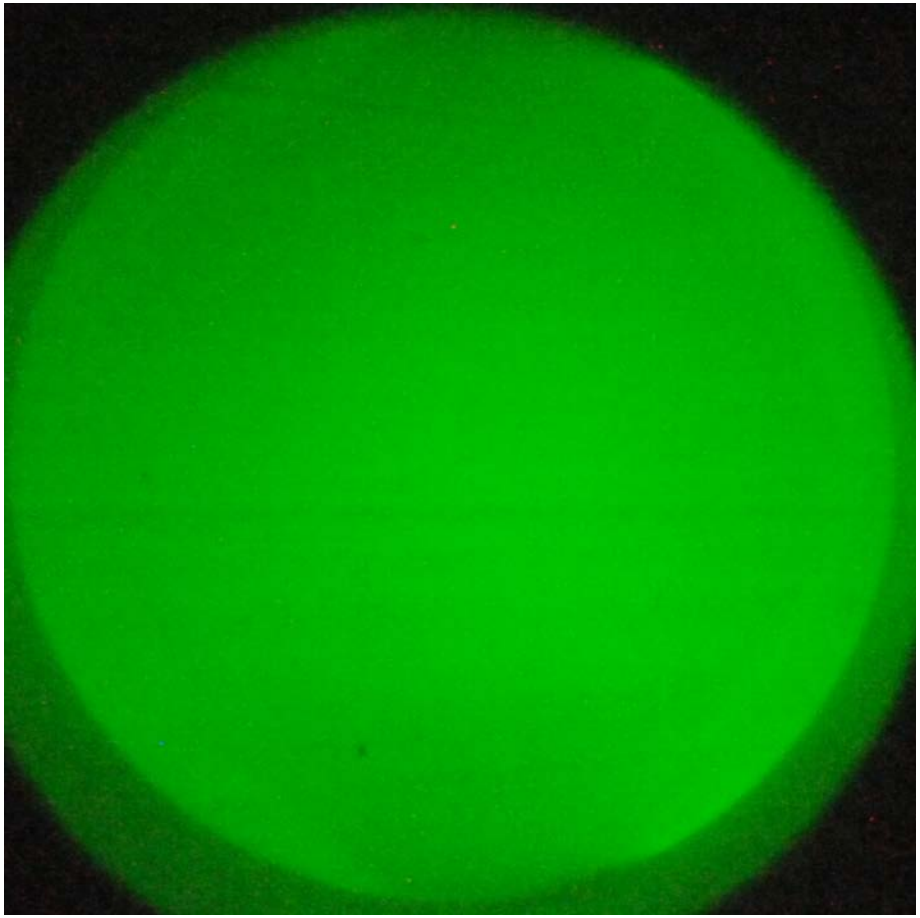


Raw image

Sample Case – N6_J30_D12

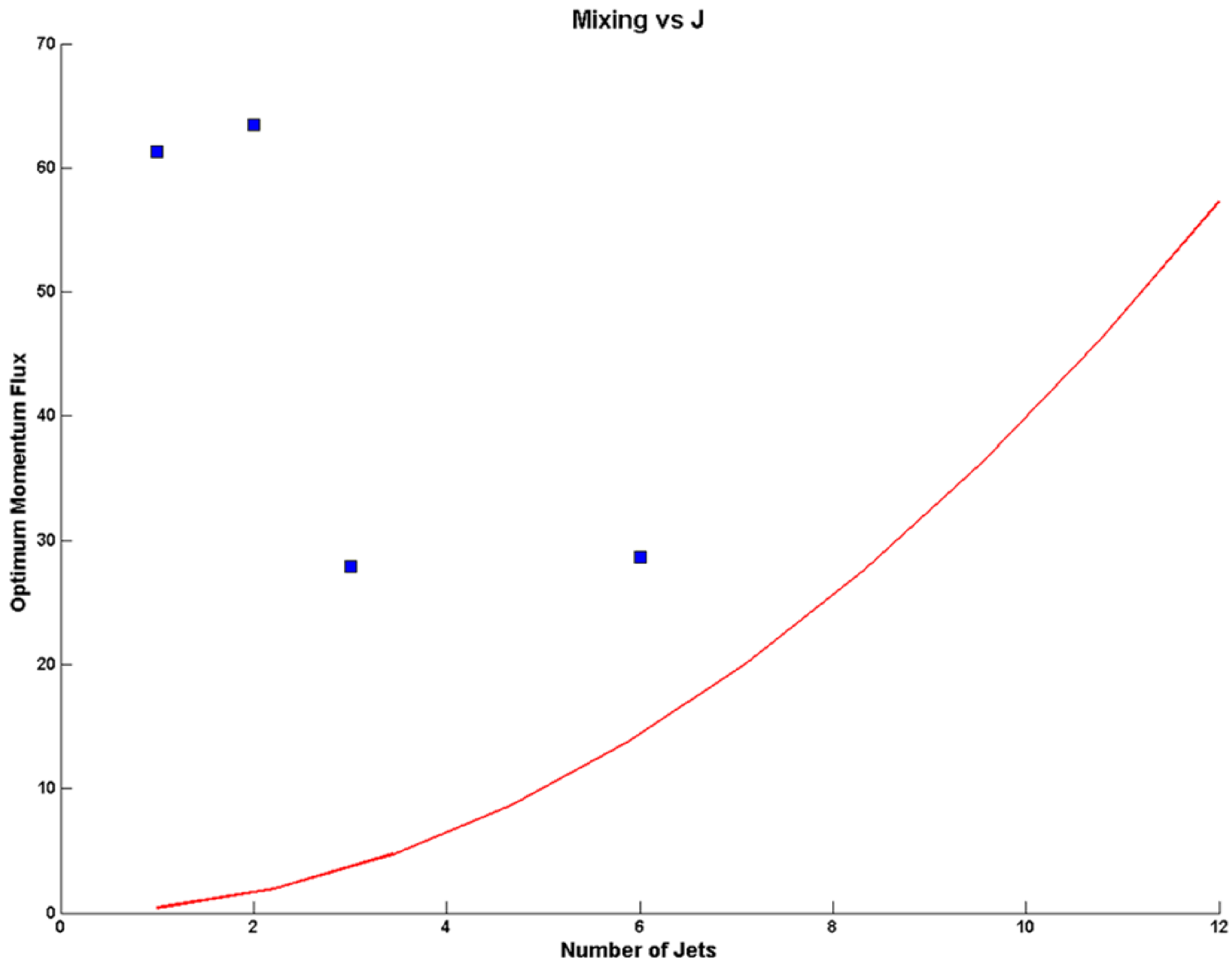


Processed image with contours



Raw image

Holdeman Plot



Conclusions

- **Sparse multi-JICF behave much how we expect**
- **Break-off point with Holdeman scaling slightly higher than theory predicts ($2\pi \sim 6.28$)**
- **Diminishing returns moving from 3 to 6 jets**
- **Take-away: there is an optimum J-value for the six-jet configuration near J = 30**

Future Work

- Obtain remainder of data for higher diameter ratios*
- Look at other axial locations for promising cases*
- Re-evaluate data anomalies
- Write a thesis? (no big deal)

*Themis work

Lessons Learned (Gripes)

- **Government work is just as slow as everyone jokes**
- **Experimentation is full of headaches**
  - Tight fitting of jet inserts with injection block
  - Determining appropriate concentration
  - Rusty tanks
  - Old pressure transducers
  - Leaks, leaks, leaks
  - Having to explain to safety that fluorescein is less dangerous than vacuum pockets
  - Fixing Labview (and logistics of dealing with IT)
  - Doing it all on a shoestring budget
- **Just use gases, they're way more simple**

Project Themis:
Water Visualization Study

Cal Poly
Dr. Tina Jameson (chair)
Dr. Dianne DeTurris
Dr. David Marshall

AFRL
Dr. Rich Cohn
Nils Sedano
Dr. David Forliti

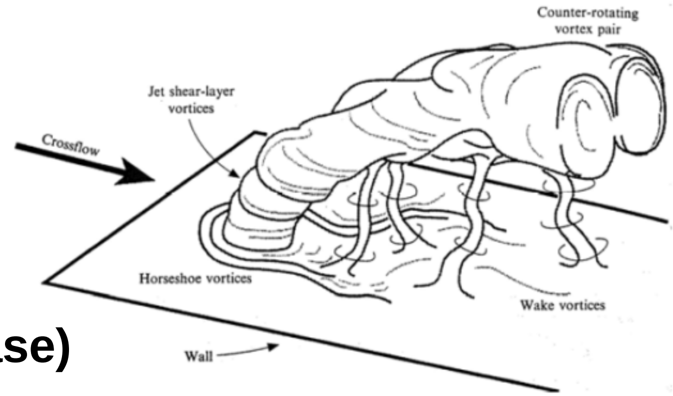
Back-Ups

Transverse Jets

Unconfined single transverse jets (single phase)

- Exhaust stacks, V/STOL aircraft, 3D canonical flow
- Studied extensively in literature
  - Fric and Roshko (1994) cited 358 times
  - Smith and Mungal (1998) cited 201 times
  - Yuan, Street and Ferziger (1999) cited 155 times
  - Margason review article (1993) cited 165 times
- Multiple vortex structures
- Scaling laws

From Fric and Roshko



Unconfined single transverse jets (two phase)

- Atomization of liquid jets
- Supersonic gas-phase velocities (Scramjet application)

Confined multiple transverse jets

- Motivated to support gas turbine combustor design
- Holdeman (NASA Glenn) and coworkers major contributor

Transverse Jet Anatomy

- Counter-rotating Vortex Pair (CVP)
- Horseshoe vortex forms at forward stagnation point
- Wake vortices shed from jet
- Occur over a wide range of Reynolds numbers

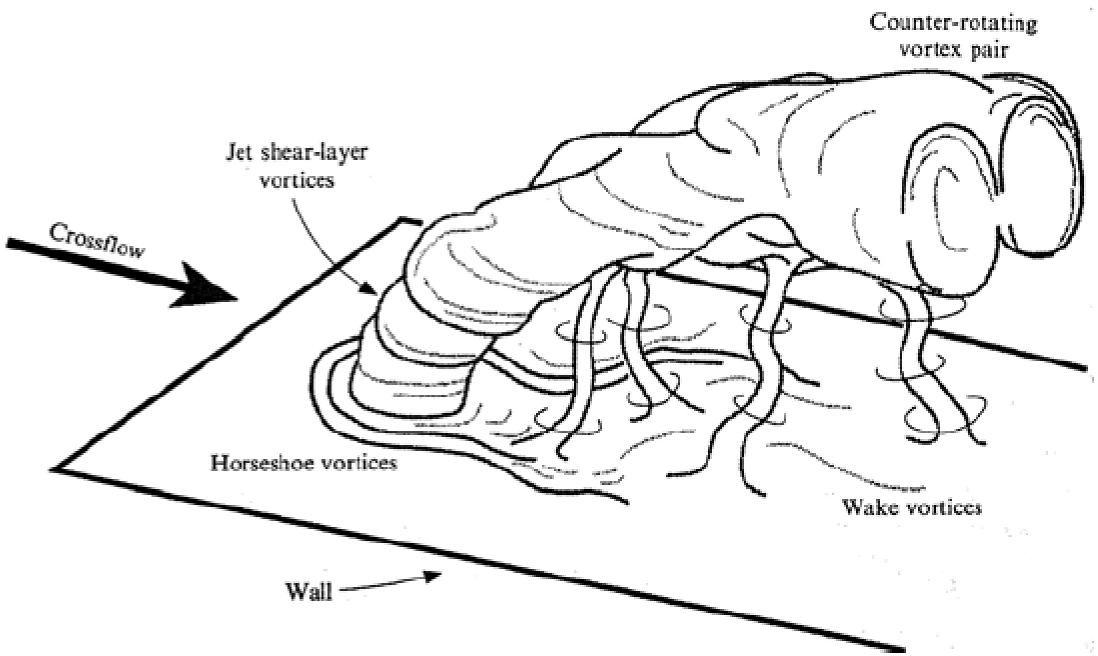


Image Credit: Fric and Roshko (1994)

Problem Statement

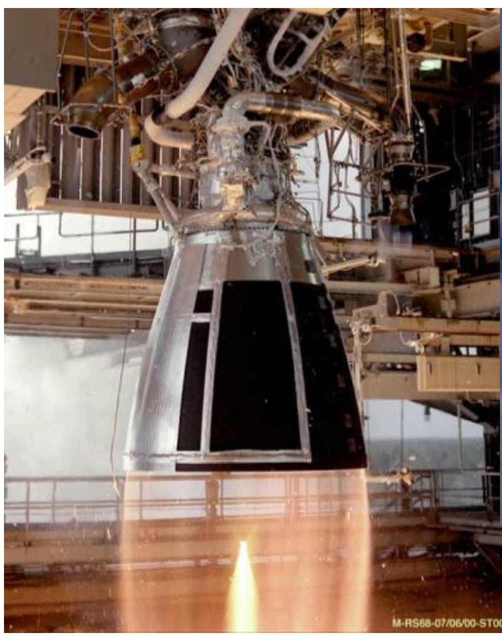
Current US Launch Systems

Delta IV (Boeing/ULA)

- First Stage: 1 RS-68
- Propellants: LOX/LH2

Atlas V (Lockheed Martin/ULA)

- First Stage: 1 RD-180
- Propellants: LOX/RP-1



Parameters and Scaling Laws

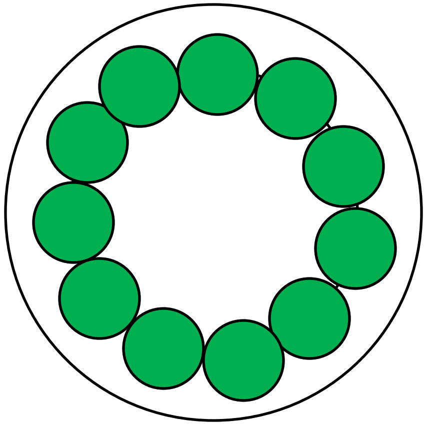
Physical argument for the Holdeman parameter

For good mixing, jet penetration ~ Radius

$$l_c^2 U_c^2 = D_j^2 U_j^2$$

$$l_c^2 \propto R_c D_j \quad \text{~ blockage}$$

$$D_J r^2 \propto R_c$$



Jet length scale is rD$_j$:

- Jet strongly deflected in a streamwise length of rD$_j$
- Jet growth to a width of ~rD$_j$

Smith and Mungal (1998)

Good mixing:

Jets far enough apart to allow CVP to form

Jets close enough to begin to merge when they approach a size of rDj

$$\left.\begin{array}{l} D_J r \propto S \\ D_J r^2 \propto R_c \end{array}\right\} \quad Sr \propto R_c \quad \text{argue} \quad r \propto J^{1/2} \quad \Rightarrow \quad C = \frac{S}{R_c}\sqrt{J}$$

ND Groups

- Used Buckingham-Pi to determine relevant dimensionless parameters
- Relevant equations:

Continuity	Momentum	Total Momentum
$\dot{m}_j = \rho_j A_j v_j$	$\rho_j A_j {v_j}^2$	$\rho_j A_j {v_j}^2 n_j$
$\dot{m}_c = \rho_c A_c v_c$	$\rho_c A_c {v_c}^2$	$\rho_c A_c {v_c}^2$

- Recurring Variables:

  $\rho_j \; \rho_c \; v_j \; v_c \; d_j \; d_c \; n_j$

- Other Variables

  $\mu_j \; \mu_c$

Parameters of Interest

ND Parameter	Equations	Notes
Momentum Flux Ratio	$J = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2$	Prominent in literature
"Kappa"	$\kappa = \sqrt{\left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)}$	Proportional to rD scaling
"Lambda"	$\lambda = \sqrt{\left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)n_j}$	Proportional to rD scaling
"Alpha"	$\alpha = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)$	Proportional to r^2D scaling
"Epsilon"	$\varepsilon = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)n_j$	Proportional to r^2D scaling
Momentum Ratio	$\beta = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)^2$	Prominent for certain jet types
Total Momentum Ratio	$\psi = \left(\frac{\rho_j}{\rho_c}\right)\left(\frac{v_j}{v_c}\right)^2\left(\frac{d_j}{d_c}\right)^2 n_j$	Accounts for jet interaction

Laser Doppler Velocimetry (LDV)

- Use interference patterns and Mie scattering to calculate bulk flow velocity
- Using geometry, the fringe spacing δ can be determined from laser wavelength and convergence angle θ:

$$\delta = \frac{\lambda}{2\sin\left(\frac{\theta}{2}\right)}$$

- Whenever a scattering particle crosses one of these interference planes, it will be sensed by a photodetector

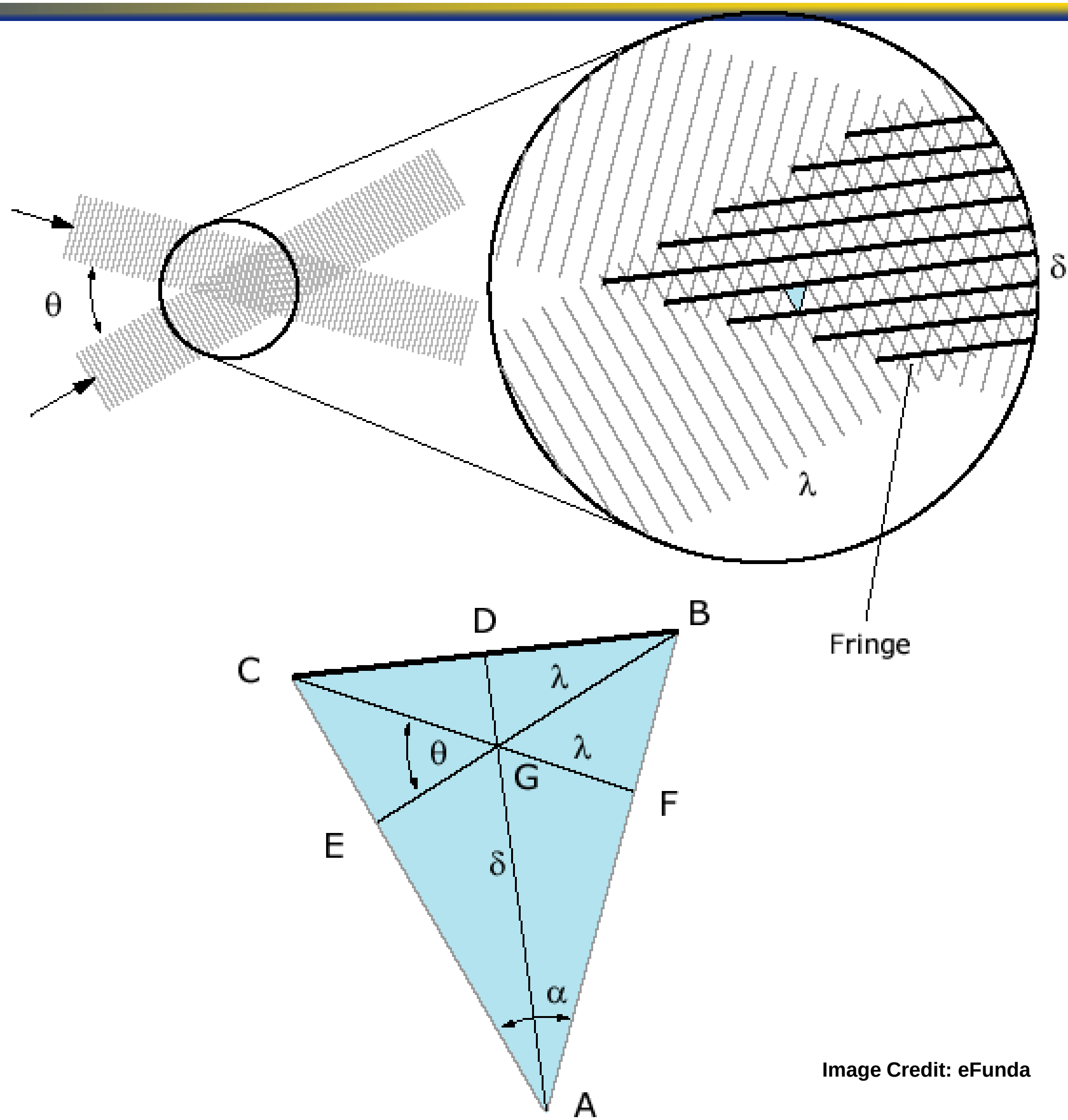


Image Credit: eFunda

Laser Doppler Velocimetry

- Particles will periodically pass through interference planes (not continuously)
- This corresponds to the Doppler burst frequency: $f_D = \frac{v_N}{\delta}$ where v_N represents the component of velocity normal to the interference plane
- Limitations:
  - Cannot predict direction
  - True velocity must be estimated by normal component
- Advantages:
  - Relatively simple
  - Non-intrusive

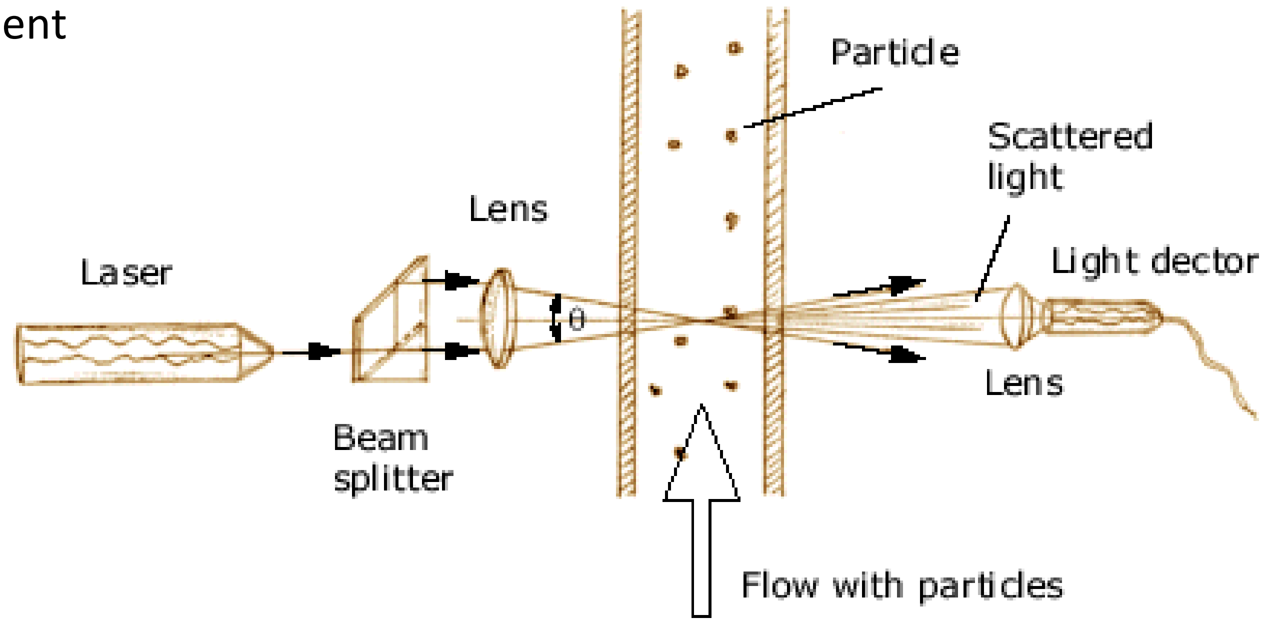
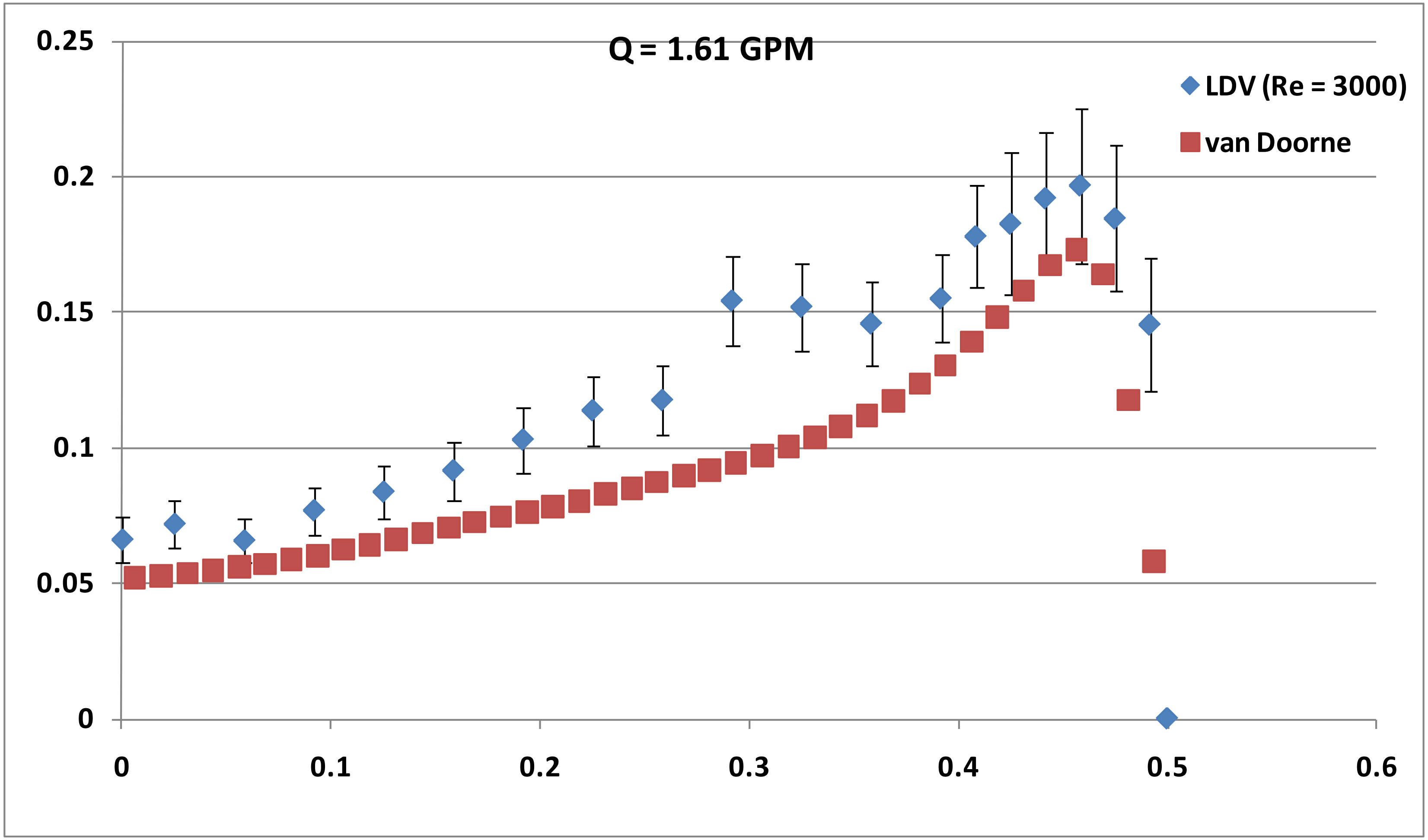
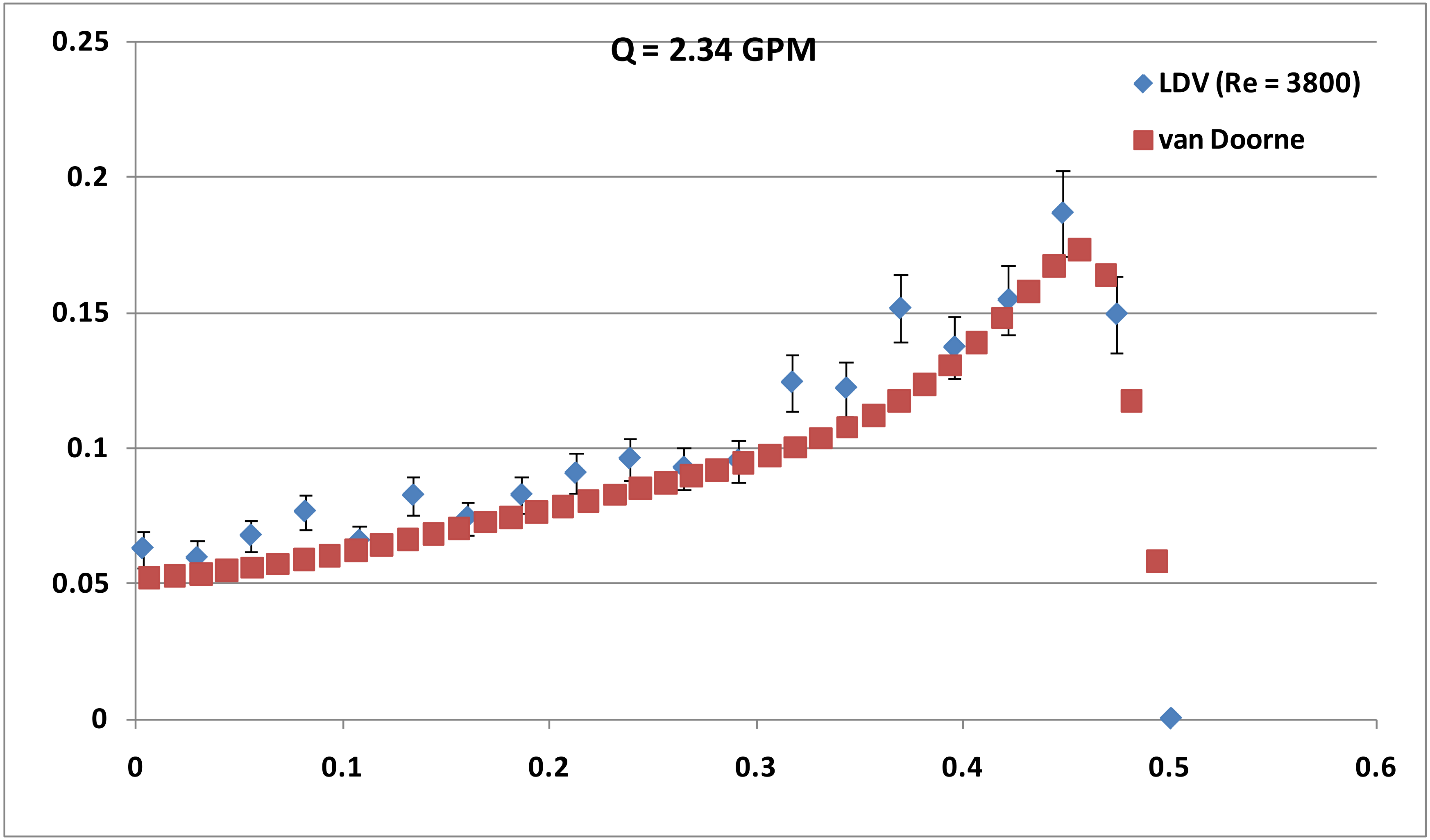


Image Credit: eFunda

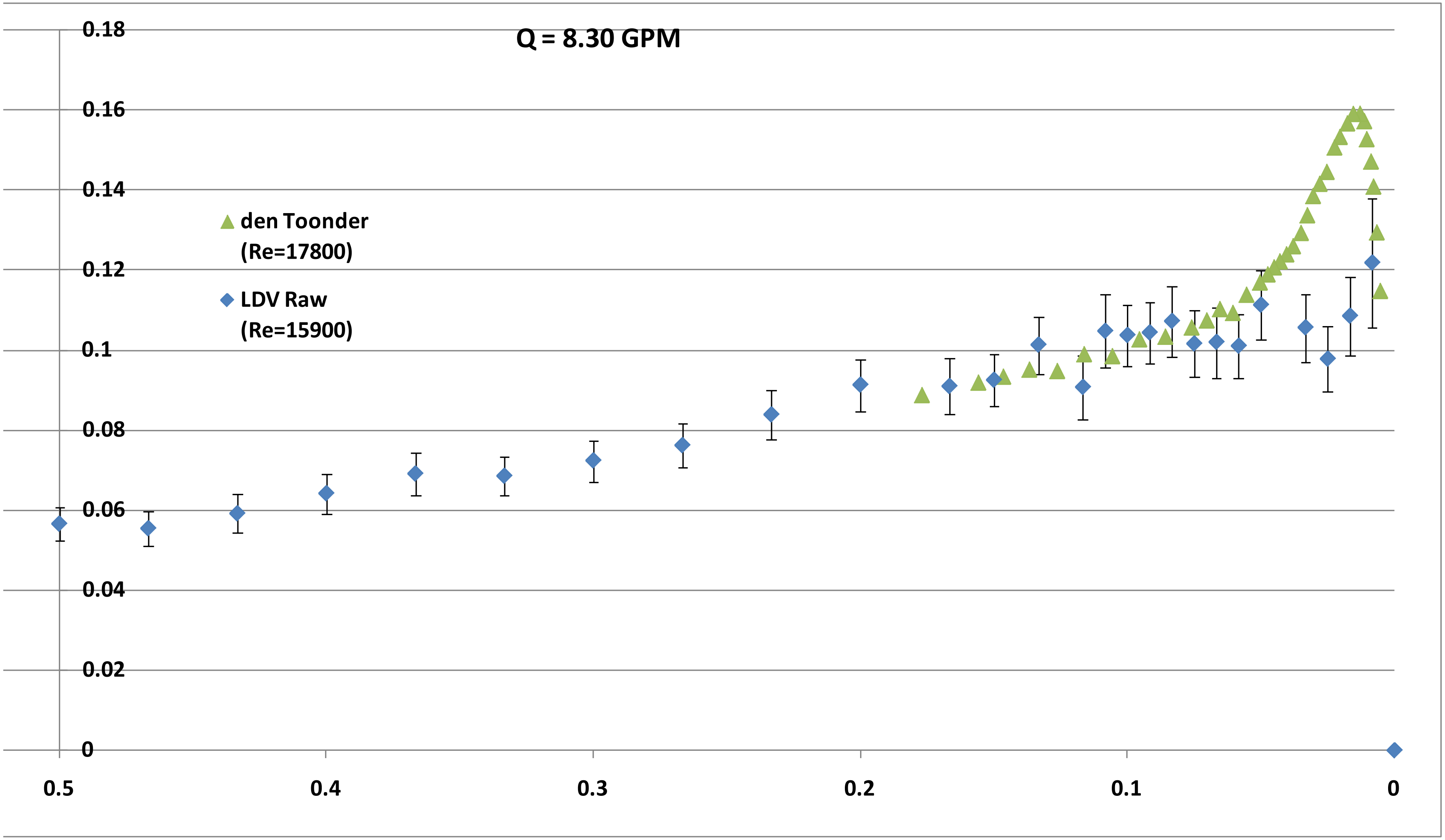
LDV Profiles



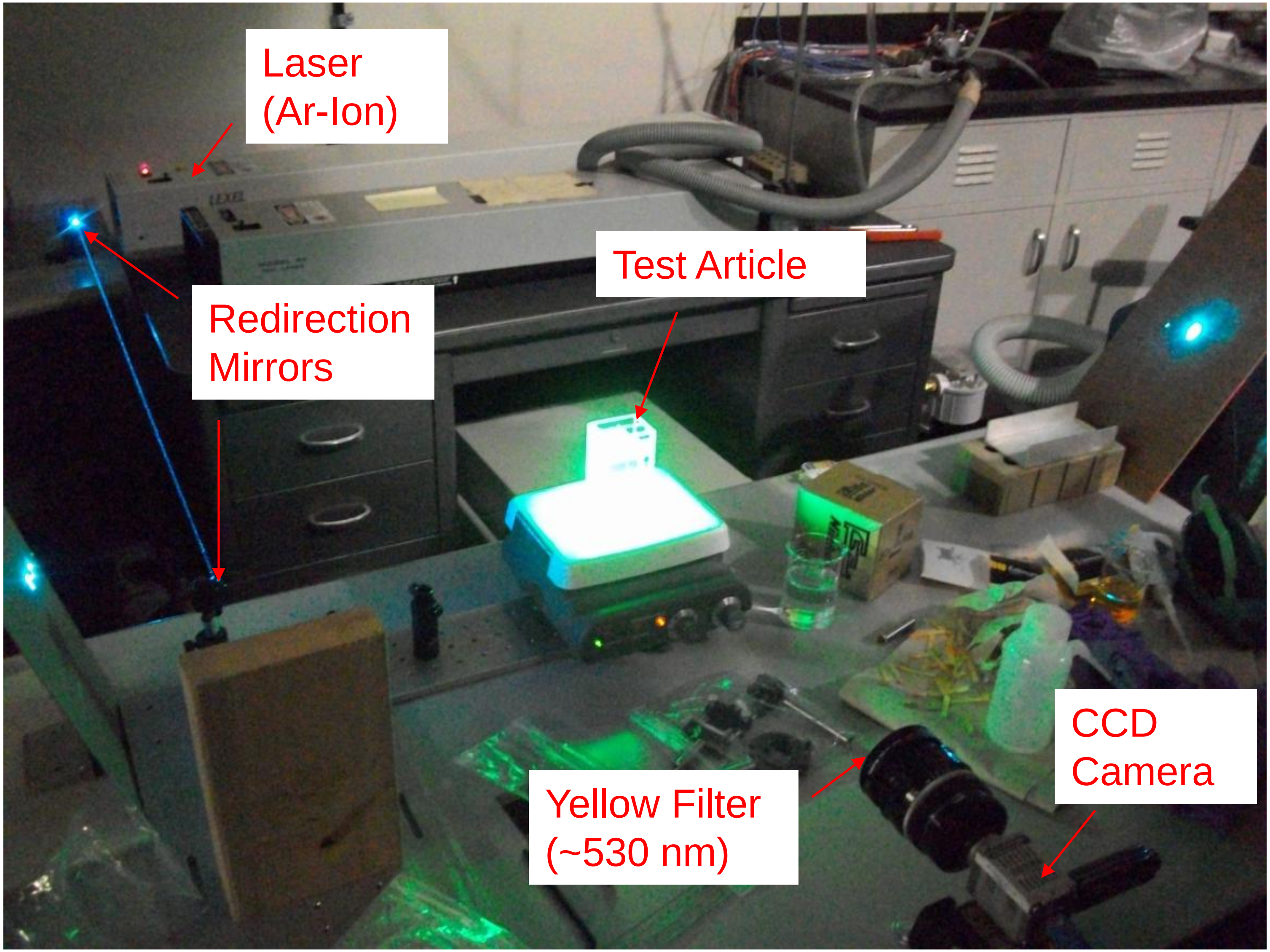
LDV Profiles



LDV Profiles

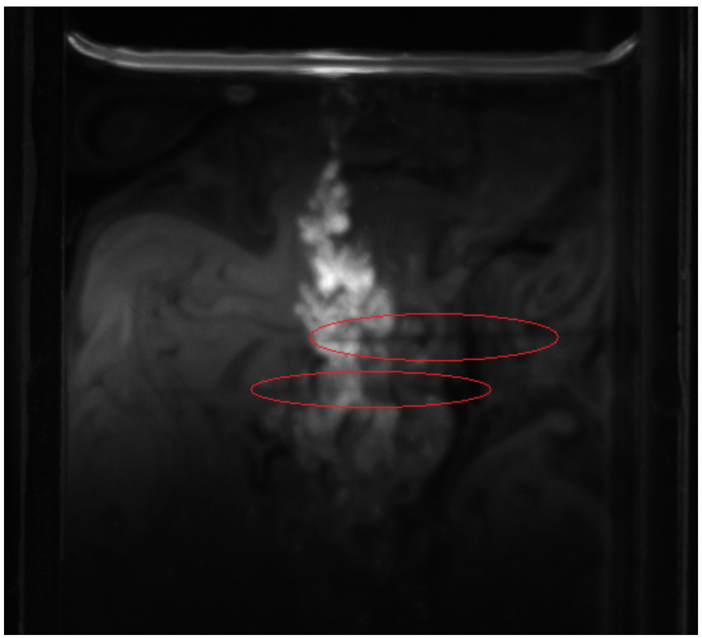


Sample PLIF Setup



General PLIF Considerations

- Fluid pH > 9
- Photobleaching
- Fluid purity
- Laser power
- Beam/sheet attenuation
- Camera
- Environment and background correction



Shadow streaking as a result of fluid impurities